A CERCLA-BASED DECISION SUPPORT SYSTEM FOR ENVIRONMENTAL REMEDIATION STRATEGY SELECTION

2Lt Brian J. Grelk

AFIT/GOR/97M-10

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY
AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

AFIT/GOR/ENS/97M-10

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Brian J. Grelk, B.S.

Second Lieutenant, USAF

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Student: Brian J. Grelk, Second Lieutenant, USAF Class: GOR-97M

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Committee:	Name/Title/Department	Signature
Advisor	Jack A. Jackson Jr., Lieutenant Colonel, USAF Assistant Professor of Operations Research Department of Operational Sciences	
Reader	Jack M. Kloeber Jr., Lieutenant Colonel, USA Assistant Professor of Operations Research Department of Operational Sciences	
Reader	Richard F. Deckro Professor of Operations Research Department of Operational Sciences	

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The opinions stated in this document are solely those of the author and do not reflect the opinions of the Air Force or the Department of Defense. In addition, the technologies and other criteria represented in this document were selected to support development of the model presented in this document. The scores assigned to the technologies, the scoring functions used, the criteria, and the weights assigned to the various criteria do not necessarily represent the opinions or positions of either the Environmental Protection Agency, the State of Idaho Department of Environmental Quality, or the Department of Energy.

DISCLAIMER

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Abstract

The Idaho National Environmental Engineering Laboratory (INEEL), operating in conjunction with the Department of Energy (DOE), faces the complex decision of selecting an environmental remediation strategy for the Subsurface Disposal Area (SDA) of the Radioactive Waste Management Complex (RWMC). This research uses value-focused thinking and multiattribute preference theory techniques to produce a decision analysis model to aid the decisionmakers as they select a remediation strategy. A deterministic analysis using expert opinion and the best available engineering data demonstrates the model's capabilities. The model ranks 27 specific remediation strategies based on how well they meet CERCLA's five balancing criteria: implementability, short-term effectiveness, long-term effectiveness, reduction of toxicity, mobility, or volume through treatment, and cost. The model allows for sensitivity analysis to display the effects of changes in engineering opinion, the values of the data, and model parameters. Overall, the model provides decision tools that can help the decisionmakers at INEEL make a better informed and better documented decision when choosing a remediation strategy. Furthermore, the model can be easily manipulated and applied by decisionmakers at other DOE sites.

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1. Introduction

1.1 Background

The Department of Energy's Environmental Management (DOE-EM) division was formed in 1989 to manage the waste and cleanup the contamination from over 50 years of nuclear weapons production and research at 137 DOE sites (DOE/EM-0228, 1995: 1). The DOE must safely manage approximately 3.1 million cubic meters of radioactive waste and materials until treatment and disposal facilities are available (DOE/ID-10513, 1995: 4). In addition, over 7,000 contaminated buildings owned by DOE require monitoring and surveillance until they can be safely decommissioned and dismantled (DOE/EM-0228, 1995: 1). This environmental restoration process will be long and expensive. The DOE reports that recent budget projections for environmental restoration are $5.5 billion for the year 2000 (DOE/EM-0228, 1995: iii) and between $200 and $300 billion for the period from 1995 to 2070 (DOE/EM-0119, 1995: xiv).

One DOE site scheduled for remediation is the Subsurface Disposal Area (SDA) at the Radioactive Waste Management Complex (RWMC) operated by the Idaho National Environmental Engineering Laboratory (INEEL). Historical records show that from 1952

to 1984 6,800,000 cubic feet of volatile organic compounds (VOCs), transuránic (TRU) contaminated wastes, low level wastes (LLW), heavy metals, and activated metals were buried in a series of pits and trenches located in the area known as SDA (INEL-95/199, 1995: 3). Trenches of an average width of 7 feet and up to 1800 feet in length were generally excavated to bedrock at a depth of approximately 10 feet. Pits were also excavated to bedrock and generally back filled with 2 to 5 feet of soil to provide a level floor. The surface areas and volumes of these pits varied widely (see Appendix A) (Arrenholz and Knight, 1991: 3).

From 1952 to 1963 workers stacked waste containers (mainly steel drums and wooden and cardboard boxes) into the pits and trenches to optimize disposal space. However, from 1963 until 1969 workers randomly dumped the waste into the pits and trenches to minimize radiation exposure (Arrenholz and Knight, 1991: 3). After dumping the waste, workers covered the pits and trenches with at least three feet of silty clay soil (Guay, 1989).

A major problem at the site is the original containers are either completely degraded or degraded enough to leak their contents. The leaking containers have resulted in contamination of an additional 11,563,000 cubic feet of soil surrounding the waste and 6,200,000 cubic feet of soil underneath the waste (INEL-95/199, 1995: 5).

Currently there are no means of containing the waste. Thus some of the waste constituents, particularly organic compounds and radionuclides (EG&G Idaho, 1989), have migrated away from the SDA leading to potential groundwater contamination (DOD/ID-10513, 1995: 6).

1.1.1 Remediation Objectives

The INEEL must remediate or clean up the SDA to the level of existing and evolving statutory and regulatory requirements (DOE/ID-10513, 1995: 6). On December 9, 1991 the DOE, the Environmental Protection Agency (EPA), and the State of Idaho Department of Health and Welfare signed a Federal Facility Agreement and Consent Order (FFA/CO) for the SDA to protect human health and the environment (INEL-95/0135, 1995: xx). This order requires decisionmakers at INEEL to determine a technology strategy that remediates the site and meets nine specific criteria defined in the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA).

1.1.2 CERCLA Criteria

CERCLA was signed in 1980 and amended in 1986. The act incorporates into law the environmental remediation procedures and clean-up standards for all sites placed on the national priorities list. Essentially the act outlines the remedial investigation/ feasibility study (RI/FS) process where the liable party selects a strategy for remediating a hazardous waste site. During the RI/FS process each remediation strategy is qualitatively ranked according to how well it meets the nine specific CERCLA criteria.

The CERCLA criteria are separated into three categories: threshold, modifying, and balancing. All strategies must meet the threshold criteria to warrant further consideration. Modifying criteria apply after the decisionmakers at INEEL announce their selected remedial strategy to the public. Finally, the decisionmakers rank the strategies relative to their ability to meet the balancing criteria. Figure 1.1 shows all three categories of criteria and the subsequent sub sections further explain each category.

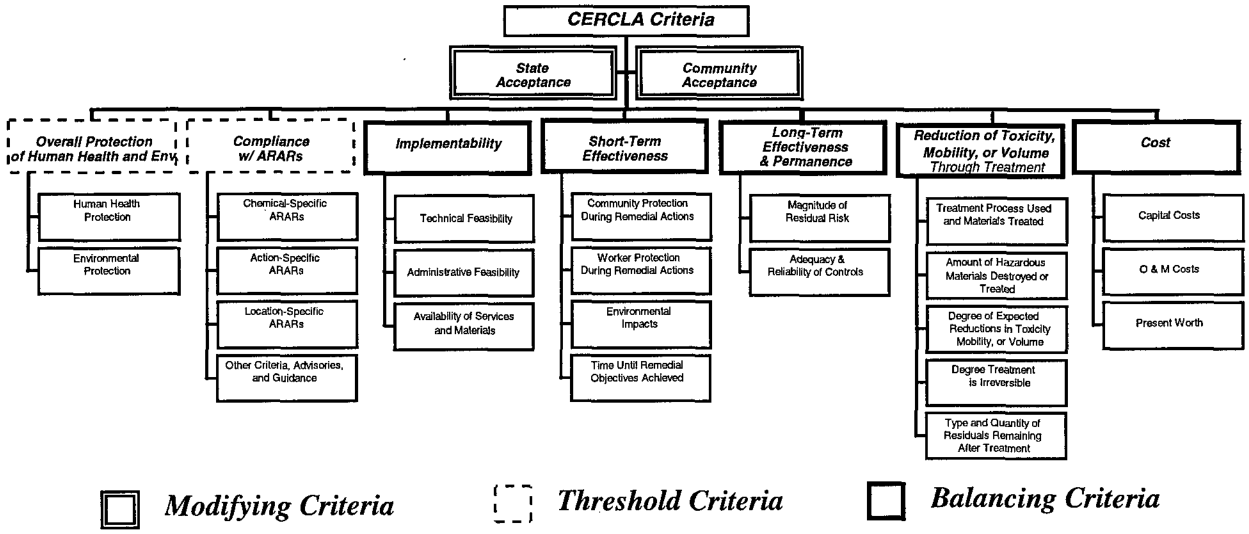


Figure 1.1 CERCLA criteria hierarchy (EPA/540/G-89/004, 1989: 6-7).

1.1.2.1 Overall Protection of Human Health and the Environment

The overall protection of human health and the environment criterion describes how the remediation strategy, as a whole, achieves and maintains protection of human health and the environment. This overall assessment of protection draws on the assessments conducted under other evaluation criteria: long-term effectiveness and permanence, short-term effectiveness, and compliance with applicable or relevant and appropriate requirements (ARARs). This is a threshold requirement in that *all* alternatives *must* meet this requirement to warrant further consideration (EPA/540/G-89/004, 1989: 6-6).

1.1.2.2 Compliance with Applicable or Relevant and Appropriate Requirements

Like the previous criterion, the compliance with applicable or relevant and appropriate requirements (ARARs) is a threshold criterion. Specifically, this criterion ensures each remediation strategy meets all of its federal and state applicable or relevant and appropriate requirements (as defined in CERCLA Section 121) identified in prior

stages of the RI/FS process. If an ARAR is not met, there must be a basis for justifying a waiver to warrant further consideration of the remediation strategy (EPA/540/G-89/004, 1989: 6-6).

1.1.2.3 Long-Term Effectiveness and Permanence

The long-term effectiveness and permanence criterion ensures the risks remaining after remediating the site are at acceptable levels. The primary focus of this criterion is the extent and effectiveness of the controls that may be necessary to manage the risk posed by treatment residuals and/or untreated wastes. Each alternative must address the magnitude of the residual risk remaining from untreated waste or treatment residuals at the conclusion of remediation activities and the adequacy and reliability of controls used to manage such wastes (EPA/540/G-89/004, 1989: 6-8).

1.1.2.4 Short-Term Effectiveness

The short-term effectiveness criterion addresses the effects of the alternative during the construction and implementation phase of the remediation process. Each alternative must address the following factors (EPA/540/G-89/004, 1989: 6-9):

- Protection of the community during remedial actions.
- Protection of workers during remedial actions.
- Environmental impacts.
- Time needed to remediate the site.

1.1.2.5 Reduction of Toxicity, Mobility, or Volume Through Treatment

The reduction of toxicity, mobility, or volume through treatment criterion addresses the statutory preference for selecting remedial actions employing treatment technologies that permanently and significantly reduce toxicity, mobility, or volume of the principal threats; wastes posing a significant threat to human health and the

environment should exposure occur. Each alternative must focus on the following specific factors (EPA/540/G-89/004, 1989: 6-6):

- The amount of principal threats the alternative destroys or treats.
- The degree of expected reduction in toxicity, mobility, or volume measured as a percentage of reduction.
- The degree to which the treatment is irreversible.

1.1.2.6 Implementability

The implementability criterion addresses the technical and administrative feasibility of implementing an alternative and the availability of various services and materials necessary during the remediation process. Each alternative must address the following (EPA/540/G-89/004, 1989: 6-9):

- Technical feasibility.
- Administrative feasibility.
- Availability of services and materials.

1.1.2.7 Costs

The cost criterion addresses the costs of a remedial strategy. Costs associated with an alternative include: capital costs and operation and maintenance costs expressed in present worth. Capital costs consist of direct and indirect costs associated with initiating the remediation alternative. Operations and management costs are post construction costs necessary to ensure the continued effectiveness of a remedial action. Finally, a present worth analysis evaluates expenditures occurring over different time periods by discounting future costs to a common base year. Such an analysis compares the remediation costs based on a single value representing the amount of money that, if invested in the base year and disbursed as needed, would cover the costs associated with the remedial action over its planned life (EPA/540/G-89/004, 1989: 6-11 to 6-12).

1.1.2.8 State Acceptance

The remediation strategy must address concerns identified by the State of Idaho during its review of the final RI/FS work plan. This review shall consider the proposed use of waivers, alternative selection process, and other actions. The remedial evaluation shall incorporate comments received from the State. This criterion is called a modifying criterion because it applies only after the detailed analysis of the alternatives but can *modify* the decision to comply with state needs and requirements (EPA/540/G-89/004, 1989: 6-13).

1.1.2.9 Community Acceptance

Each remediation alternative's evaluation must assess community acceptance. Complete assessment is not possible until comments are received on the proposed action. However, the community should be involved throughout the entire process. This criterion is also considered a modifying criterion (EPA/540/G-89/004, 1989: 6-13).

1.1.3 Remediation Alternatives

Decisionmakers at INEEL have six categories of actions, called general response actions, from which to choose when remediating the SDA. These general response actions contain several technologies, called process options, which may be used independently or in combination with process options from other general response actions, to ensure CERCLA compliance. The following sections list the general response actions and provide descriptions of each. Specific combinations of process options evaluated in this research are presented later in this document.

1.1.3.1 No Action

No action consists of monitoring the site without taking any direct action to treat, stabilize, or remove the contaminants. This alternative only applies if there is no risk from contamination, however CERCLA states this action must be evaluated during the RI/FS stage (INEL-95/0343, 1995: 5-11).

1.1.3.2 Institutional Controls

Institutional controls prevent or limit access to contaminated areas through the period of time that DOE maintains ownership of the SDA. This period would include administrative procedures, deed restrictions, fences or other barriers, signs, and security (INEL-95/0343, 1995: 5-11).

1.1.3.3 Containment

Containment reduces risks from chemical and radiological contaminants to acceptable levels without removing contaminants from the site. Containment prevents erosion of subsurface soils and reduces infiltration of contaminants though the soil to the groundwater (INEL-95/0343, 1995: 5-11).

1.1.3.4 In-Situ Treatment

In-situ treatment also reduces risks from chemical and radiological contaminants to acceptable levels without removing them from the site. However, this action differs from containment because it includes a means of stabilizing the waste to ensure contaminant migration to the surface or groundwater maintains at an acceptable level (INEL-95/0343, 1995: 5-16).

1.1.3.5 Retrieval, Ex-Situ Treatment, Storage, and Disposal

Retrieval, ex-situ treatment, storage, and disposal consists of retrieving the overburden, waste, and possibly underburden. Waste meeting protectiveness standards are returned to the waste area. Material not returned is treated either physically or chemically and stabilized (if necessary) to meet disposal facility requirements. This action may require interim storage for the material waiting for treatment (INEL-95/0343, 1995: 5-16).

1.1.3.6 Retrieval, Storage, and Disposal

Retrieval, storage, and disposal consists of retrieving the overburden, waste, and possibly underburden. Wastes meeting protectiveness standards are returned to the waste area. Contaminated media is stabilized and packaged to meet acceptance criteria at a disposal facility. This alternative does not include treatment beyond stabilization and is only viable if a facility is licensed to accept the waste without treatment (INEL-95/0343, 1995: 5-16).

1.2 Problem Statement

Decisionmakers at INEEL require a decision analysis tool incorporating life cycle cost and technology performance to assist them in the RI/FS process. This tool should assist the decisionmakers in selecting remediation strategies based on their performance towards the five CERCLA balancing criteria at the SDA site.

1.3 Research Objectives and Scope

This research provides decisionmakers at INEEL a deterministic decision analysis model quantifying each remediation strategy's ability to meet the CERCLA criteria. The

model uses value-focused thinking fundamentals, multiattribute preference theory, and decision analysis techniques such as: fundamental objectives hierarchy, component value functions, additive value functions, and sensitivity analysis to analyze each remediation strategy against the CERCLA balancing criteria.

The emphasis of this research is insuring the model provides maximum benefit to the decisionmakers. Using outputs such as overall value, cost versus performance scatter plots, sensitivity graphs, and tornado and rainbow diagrams allow the decisionmakers to easily identify dominant strategies and tradeoffs between strategies and the balancing criteria.

The model created during this research is the first stage of a combined effort between MSE, Virginia Commonwealth University (VCU), and the Air Force Institute of Technology (AFIT). VCU will lead the second stage of this effort using the results from this (AFIT's) analysis to: improve the CERCLA hierarchy metrics, modify and score alternatives as necessary, update data, and provide an uncertainty analysis (Parnell, 1996). MSE is responsible for generating remediation strategy life cycle cost data used in these models and will provide updated costs for the VCU analysis in the future.

1.4 Approach

This research begins by applying value-focused thinking fundamentals to structure the decisionmakers' goals in a fundamental objective's hierarchy. Structuring the decisionmakers' objectives in this way provides the basis for quantitative modeling (Keeney, 1992: 69). Decision analysis tools model the CERCLA driven fundamental objectives hierarchy while preference theory quantifies decisionmaker values. The model

combines life cycle costs and technology performance evaluation measures, based on previous remediation efforts and/or expert opinion, for each remediation strategy. Next, the model ranks the remediation strategies based on their expected value to the decisionmakers. Finally, sensitivity analysis of technology parameters and criteria weights provide the decisionmakers additional information about the robustness of top ranked strategy.

1.5 Overview

Chapter Two reviews the fundamentals and principals of value-focused thinking, preference theory, and decision analysis. Chapter Three provides the decisionmakers' fundamental objective's hierarchy and associated weights, the component value functions, and the corresponding decision analysis model from the methods reviewed in Chapter Two. Chapter Four analyzes the model's output for the SDA site data. Finally, Chapter Five provides conclusions and recommendations for site remediation and follow-on work.

2. Literature Review

2.1 Introduction

This literature review begins by introducing decision analysis and exploring its usefulness towards environmental decisionmaking. Next, this review explores three aspects of decision analysis used to aid decisionmakers: value-focused thinking, multiattribute preference theory, and modeling. After reading this review the reader should understand how value-focused thinking and multiattribute preference theory can be incorporated into a decision analysis model that aids the decisionmaker.

2.2 Decision Analysis

Decision analysis is a powerful technique used to aid decisionmakers facing difficult decisions. Figure 2.1 illustrates the types of problems decision analysis is designed to handle, marking appropriate decision analysis applications with an 'X'. As the figure shows, decision analysis is a prescriptive method designed for difficult decisions with complex structures consisting of several uncertain variables. In addition, decision analysis incorporates the decisionmakers' values and attitudes towards taking risks. Finally, decision analysis applies to decisions with either singular or multiple, and potentially conflicting, objectives.

Environmental remediation problems are very difficult problems and can benefit from decision analysis techniques for several reasons. First, environmental remediation decisions are often very complex due to numerous alternatives, their possible combinations, and the resulting effectiveness of the combinations. Decision analysis provides methods for structuring complex problems (decision trees and influence

diagrams) that clearly show possible courses of action, the possible outcomes that may result, as well as the likelihood of those outcomes, factors influencing and affected by such outcomes, and the eventual consequences that can occur from the different outcomes (Clemen, 1996: 2).

Methodology	Descriptive		X Prescriptive
Decision Difficulty	Easy		X Hard
Problem Structure	Known/Simple		X Unknown/Complex
Decision Frequency	X One of a Kind		X Recurring
Problem Variables	Deterministic		X Uncertain
Number of Significant Uncertain Variables	X Small	X Medium	Large
Decisionmaker Values	X Clear		X Complex
Decisionmaker Objectives	X Single		X Multiple
Risk	X Low	X	X High

Figure 2.1 Types of problems decision analysis handles (Jackson, 1996).

Second, decision analysis can address the inherent uncertainty associated with environmental remediation problems. Decisionmakers rarely know the exact types and

quantities of waste that may be encountered during a remediation effort involving DOE sites. In addition, important information such as remediation costs, effectiveness of the technology, and the time required to remediate a site are often expressed as ranges based on expert opinion when innovative technologies are among the decision options to be applied to incompletely characterized sites. Decision analysis can model the uncertainty associated with a decision situation and identify sources of uncertainty that can change the overall decision.

Third, decision analysis can aid environmental decisionmakers in ranking alternatives based on the nine specific, but potentially conflicting, CERCLA objectives defined by law. For example, two key objectives are "protecting human health and the environment" and "community acceptance." Clearly, achieving the prior objective helps achieve the latter; however efforts to satisfy both these objectives will likely have a negative effect on another objective, minimizing costs. Decision analysis provides a framework based on multiattribute preference theory that can handle multiple, conflicting objectives (Clemen, 1996: 3) by converting evaluation measure scores into dimensionless units representing how well the measure's score meets the decisionmakers' objectives. Weights, based on the decisionmakers' preferences, are assigned to each evaluation measure. The results for each objective are then combined through a function providing the overall value of a strategy to the decisionmaker. The higher the value associated with a strategy, the more that strategy achieves the decisionmakers objectives.

Finally, decision analysis can help environmental decisionmakers address the concerns of numerous stakeholders involved in the decisionmaking process. Each

stakeholder has his or her own interests and values that may lead to conclusions different from other stakeholders. In all Superfund remediation sites there are three independent decisionmakers (the local community and state, the Environmental Protection Agency (EPA), and the Department of Energy (DOE)) with their own missions and goals. Referring to the example in the previous paragraph, citizens in the surrounding community may believe that health risks of a site should be reduced no matter what the cost. However, a lawmaker in Washington, DC must decide whether to provide all of the funding for the remediation effort, knowing that such funding may be taken from defense or medical research dollars or from remediation efforts at other locations. The framework of decision analysis, combined with its tools, can help different groups become more informed about the decision process and provide a common medium to settle differences.

2.2.1 Requirements for Decision Analysis

Jennings, Mehta, and Mohan report that decision analysis techniques apply if a problem meets four essential requirements (Jennings, Mehta, and Mohan, 1994: 1135). The first two require the analyst to know the structure of the problem. The first requirement is a known set of $n > 1$ alternatives. The second requirement is a known set of $m \geq 1$ criteria the decisionmaker must attempt to satisfy.

The third requirement is a method of evaluating decision alternatives relative to the decision criteria. This may be achieved by multiattribute preference theory, which is discussed later in this chapter, or other methods like the Analytic Hierarchy Process (AHP) and multiple criteria decisionmaking (MCDM). Regardless of the method, each

objective's quantification must be cardinal in nature, finite, and real, but may be on relative or absolute scales. The quality of the quantification procedures affects the quality of the resulting decision. However, a good decision model should function regardless of the quality of the data (Jennings, Mehta, and Mohan, 1994: 1135).

The final requirement is a method specifying the relative importance (weight) of each decision criterion. The criteria weights may be either subjective inputs dependent upon the decisionmakers' values (Jennings, Mehta, and Mohan, 1994: 1135) or specific inputs directed by law. Several methods are available to determine criteria weights; some of these methods are described in detail later in this chapter.

2.2.2 Decision Analysis in Environmental Decisionmaking

Decision analysis has become widely used in business, medicine, military science, and engineering. Although the discipline is relatively new in the environmental remediation field, decision analysis techniques have been applied to specific remediation sites. Several authors have written reports advocating its use in the CERCLA process. In fact, the CERCLA process itself "uses the fundamental concepts of decision analysis to construct a sound framework for environmental decisionmaking (Purucker et. al., 1991: 2)."

In a 1994 study, Jennings, Mehta, and Mohan compiled a list of environmental decision analysis models, adopted by government agencies, which utilize multiattribute theory. A summary of these models is provided by table 2.1.

Table 2.1 Summary of decision analysis models previously used for environmental decisions (Jennings, Mehta, and Mohan, 1994: 1133 - 1138).

Model	Agency	Description
HRS **H**azardous **R**anking **S**ystem	EPA	Placed waste sites on the National Priorities List (NPL). It is a simple model based on a composite weighted score: $S = S_M + S_{FE} + S_{DC}$ where S_M is the score for the potential to do human or environmental damage by migration, S_{FE} is the score for potential explosion or fire hazards, and S_{DC} is the score for the potential of direct contact with the hazard.
RAAS **R**emedial **A**ction **A**ssessment **S**ystem	DOE	Model developed by Pacific Northwest Laboratory (PNL) designed to link and evaluate established technology process options in support of conducting feasibility studies under CERCLA (Buelt, Stottlemyre, White, 1991:103).
POS **P**rogram **O**ptimization **S**ystem	DOE	Optimizes spending on restoration projects and allocating remediation budgetary resources. The model is based on the following utility function: $U = W_{hs}U_{hs}X_{hs} + W_{rr}U_{rr}X_{rr} + W_{pc}U_{pc}X_{pc} - W_{rc}C_{rc} - W_{fc}C_{fc}$ Where the X's are performance scores for health and safety (hs), regulatory responsiveness (rr), and public concern (pc). The U's represent functions that define the utility of each X score. The W's are the importance weights, and the C's are the remaining (rc) and future (fc) costs.
DPM **D**efense **P**riority **M**odel	DOD	Estimates the risk to human health and the environment. Makes use of weighted scores that consider the source materials and their pathways to humans and the environment. Resulting score prioritizes DOD remedial actions.
HEPRM **H**uman **E**xposure **P**otential **R**anking **M**odel		Ranks sites for New York's Superfund sites and allocates funds in New York State's Superfund program.
CORA **C**ost **o**f **R**emedial **A**ction		Assists in cost analysis of remedial actions,
PAST **P**otential **A**RAR's **S**election **T**ool		A generic model that assists decisionmakers identify ARAR's (Applicable or Relevant and Appropriate Requirements) affecting cleanup sites.
P-DAE **P**robabilistic **D**ecision **A**lternative **E**valuation		Generic model providing a ranking vector (**R**) of n alternatives (against m objectives) by multiplying a normalized utility matrix (V) by a weight vector (**W**), **VW = R.** **V** is a $n \times m$ matrix where V_{nm} = utility of the mth decision criterion for the nth decision divided by the total of utilities for all alternatives. The program uses Monte Carlo techniques to model utility uncertainties and resulting variations in **R**. Given sufficiently large runs, one may develop histograms for each of the elements of **R**, determine the probabilities of the relative rankings, or evaluate measures on solution accuracy and sensitivity.
P-DARE **P**robabilistic **D**ecision **A**lternative **R**atio **E**valuation		Generic model evaluating decision alternatives in pairs for each decision criterion. A matrix **U'** is generated from the $(n\text{-}1)m$ pairwise comparison. U'_{nm} = utility of the mth decision criterion for the nth decision alternative divided by the utility of the mth decision criterion for the $n + 1$st decision alternative. The product of all U's for each alternative creates a variable U_{nm}. The problem uses the P-DAE method to find the ranking vector **R**.

2.3 Value-Focused Thinking

Value-focused thinking can be a crucial process in decision situations where there are multiple and conflicting objectives. This method structures the decisionmakers' values and goals so a decision analysis model can identify the alternatives providing the most value to the decisionmaker. While the value-focused thinking approach is not the usual way people approach a decision, in many situations it provides a better approach capable of producing better results. Decisionmakers at the Hanford Tank Waste Remediation System have recognized this approach and applied its techniques in their on-going remediation efforts at the site (Keeney, 1996: 1).

This section begins by describing the difference between value-focused thinking when compared to the commonly used alternative-focused thinking. Next, the section describes the advantages of using value-focused thinking. Finally, this section presents the methods of value-focused thinking.

2.3.1 Value-Focused Thinking Versus Alternative-Focused Thinking

"Value-focused thinking essentially consists of two activities: first deciding what you want and then figuring out how to get it (Keeney, 1992: 4)." This is opposed to alternative-focused thinking where one creates a list of alternatives and then chooses the best alternative from the list.

Almost all decisionmakers solve problems using alternative-focused thinking (Keeney, 1992: 3); however, decisionmakers must consider *why* they are making a decision in the first place. People make decisions hoping to maximize desirable consequences and minimize undesirable outcomes. "The relative desirability of

consequences is a concept based on values. Hence, the fundamental notion in decisionmaking should be values, not alternatives. Alternatives are the means to achieve the more fundamental values (Keeney, 1992: 3)."

2.3.2 Advantages of Value-Focused Thinking

In addition to creating alternatives to the decision situation, value-focused thinking can provide much more insight and information to the decisionmaker. Figure 2.2 and the accompanying descriptions illustrate these advantages.

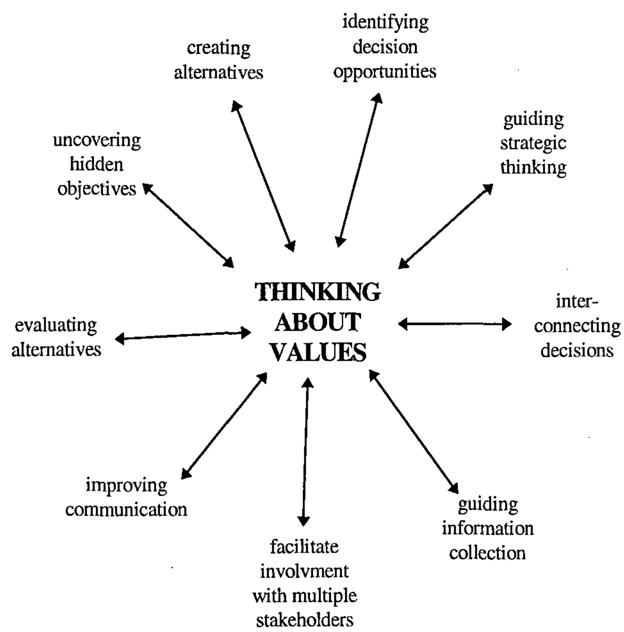


Figure 2.2 Overview of value-focused thinking (Keeney, 1992: 24).

1. **Uncovering hidden objectives.** Thinking of values may provide keys to bringing subconscious thoughts to consciousness, thus uncovering objectives not yet realized.
2. **Creating alternatives.** Creating alternatives may be more important than evaluating available alternatives. Value-focused thinking enhances the creation of desirable

alternatives by allowing the value model to guide the search for creative alternatives to the situation under consideration.

3. **Identifying a decision opportunity.** Sometimes it is preferable to identify opportunities to improve overall values before a problem occurs. Systematically appraising how well things are doing in terms of values may suggest opportunities to pursue.
4. **Guiding strategic thinking.** Strategic values do not radically change over time and provide a stable point of reference to guide all decisions over a long time horizon. Value-focused thinking compels the decisionmaker to formulate a strategic objective.
5. **Interconnecting decisions.** Explicitly stating the decisionmakers' values helps ensure that decisions are consistent. This does not mean that all alternatives must further the same specific objectives, but rather, all alternatives should further the same set of ultimate objectives.
6. **Guiding information collection.** With limited resources it is important that resources spent on gathering information provide useful data. What constitutes useful data? Data only has value if it helps lead to better consequences or avoid worse consequences, either through better alternatives or through a wiser choice from the available alternatives. Carefully quantified objectives allow calculations that determine the potential usefulness of gathering information.
7. **Facilitating involvement in multiple-stakeholder decisions.** Many situations involve multiple decisionmakers working together to produce decisions. Value-focused thinking can contribute to the productivity of such situations, particularly if

the decisionmakers have different missions. Knowing values explicitly can separate disagreements about possible consequences from disagreements about the relative desirability of those consequences. This helps identify bases for conflicts, thus providing the opportunity to reduce them.

8. **Improving communication.** Value focused thinking uses a common vocabulary about the achievement of objectives in a particular decision context. This basis should help facilitate communication and understanding.

9. **Evaluating alternatives.** Quantifying value judgments allows one to build a quantitative value model. Linking values to the model that describe consequences of various alternatives can provide inferences to the relative desirability of the alternatives. Furthermore, sensitivity analyses of the alternative's desirability to specific value judgments are possible.

2.3.3 Value-Focused Thinking Framework

The heart of value-focused thinking is, of course, values. Values are treated with such importance because they "provide the foundation for interest in any decision situation (Keeney, 1992: 55)." Properly identifying and structuring the decisionmakers' objectives is crucial because objectives explicitly state the values of concern in a given decision situation. The remainder of this sub section describes the methodology of value-focused thinking: generating objectives, separating the objectives into fundamental and means objectives, and structuring the sets of objectives.

2.3.3.1 Generating Objectives

The first step in any value-focused thinking exercise is identifying the decisionmakers' objectives for the decision situation. The following list provides Keeney's eight suggestions for generating the decisionmakers' list of objectives (Keeney, 1994: 35). The questions after the suggestions (also provided by Keeney) may be asked to aid the decisionmaker during the process.

1. **Develop a wish list.** What do you want? What do you value? What should you want?
2. **Identify alternatives.** What is a perfect alternative, a terrible alternative, some reasonable alternative? What makes these alternatives perfect, terrible, and reasonable?
3. **Consider problems and shortcomings.** What is wrong or right with your organization? What needs fixing?
4. **Predict consequences.** What has occurred that was good or bad? What might occur that you care about?
5. **Identify goals, constraints, and guidelines.** What are your aspirations? What limitations are placed on you?
6. **Consider different perspectives.** What would your competitor or your constituency be concerned about? At some time in the future, what would concern you?
7. **Determine strategic objectives.** What are your ultimate objectives? What are your values that are absolutely fundamental?

8. **Determine generic objectives.** What objectives do you have for your customers, your employees, your shareholders, yourself? What environmental, social, economic, or health and safety objectives are important?

2.3.3.2 Separating Objectives

After generating a complete list of objectives, the next step in the value-focused thinking process is separating the list into means objectives and fundamental objectives. This critical step identifies and separates objectives which help achieve other (more fundamental) objectives from those which reflect what the decisionmaker really wants to achieve (Clemen, 1996: 44).

2.3.3.2.1 Separating Fundamental Objectives and Means Objectives

One separates fundamental objectives from means objectives by examining the reasons for each item on the list. Keeney suggests that for each objective, one should ask "Why is this objective important in the decision context?" If the answer is "Because it is one of the essential reasons for interest in the situation" or "It is just important to me," then the objective is a candidate for the fundamental objective set. However, if the answer is "Because it helps achieve some other objective" then the objective is a means objective. Keeney refers to this method as the "Why is that important (WITI)?" test (Keeney, 1992: 66).

Notice that when a decisionmakers' answer to the WITI test is that the objective is one of the essential reasons for interest in the situation, the objective is considered a *candidate* for the fundamental objectives set. Since fundamental objectives are so critical to the decision context, they should be as useful as possible for creating and evaluating

alternatives, identifying decision opportunities, and guiding the decisionmaking process. In order for a candidate fundamental objective to enter the set of fundamental objectives it should be: essential, controllable, complete, measurable, operational, decomposable, nonredundant, concise, and understandable (Keeney, 1992: 82). If the candidate meets these criteria, then it is a fundamental objective. If the candidate does not meet all of the criteria, it must be written differently so it meets the criteria or becomes a means objective.

2.3.3.2.2 Structuring Fundamental Objectives

Fundamental objectives are organized into hierarchies, much like organization charts. The upper levels in a hierarchy represent more general objectives while the lower levels explain or describe important elements of the more general objective levels. Moving down the hierarchy from an upper-level objective answers the question "What do you mean by that?" Moving up the hierarchy from a lower-level answers the question "Of what more general objective is this an aspect (Clemen, 1996: 47)?"

Figure 2.3 shows a hypothetical fundamental objectives hierarchy, created by LTC Jack Kloeber, for a parent selecting the best college for his or her child. In this decision situation, the strategic objective is selecting the best available college. Three lower-level objectives: maximize college quality, minimize annual cost, and positive campus atmosphere explain what the decisionmaker means by the "best" college.

Two of the three lower-level objectives are further broken to even lower-level fundamental objectives. The decisionmaker feels that college quality is defined by the quality of the faculty and staff and the quality of the student population. In addition, the

decisionmaker feels that a good aesthetic appearance, safety, and opportunity for involvement in student activities are the fundamental components of a positive campus atmosphere.

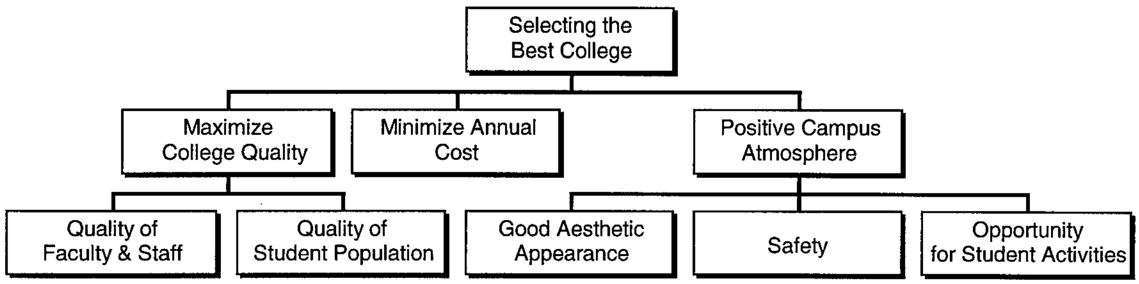


Figure 2.3 A hypothetical fundamental objectives hierarchy (Kloeber, 1996).

2.3.3.2.3 Structuring Means Objectives

Means objectives are organized into networks. Like the fundamental objectives hierarchy, the strategic objective is the foundation. However, one moves down the network by asking "How could you achieve this?" One moves up the network by asking "Why is that important?" Unlike the fundamental objectives hierarchy, which allows a lower-level objective to lead into only one higher-level objective, the means objective network allows lower-level objectives to lead into multiple higher-level objectives and similar-level objectives. Connecting different means objectives in this matter implies influence between the two objectives. The means objective network for the selecting the best college example is shown in Figure 2.4.

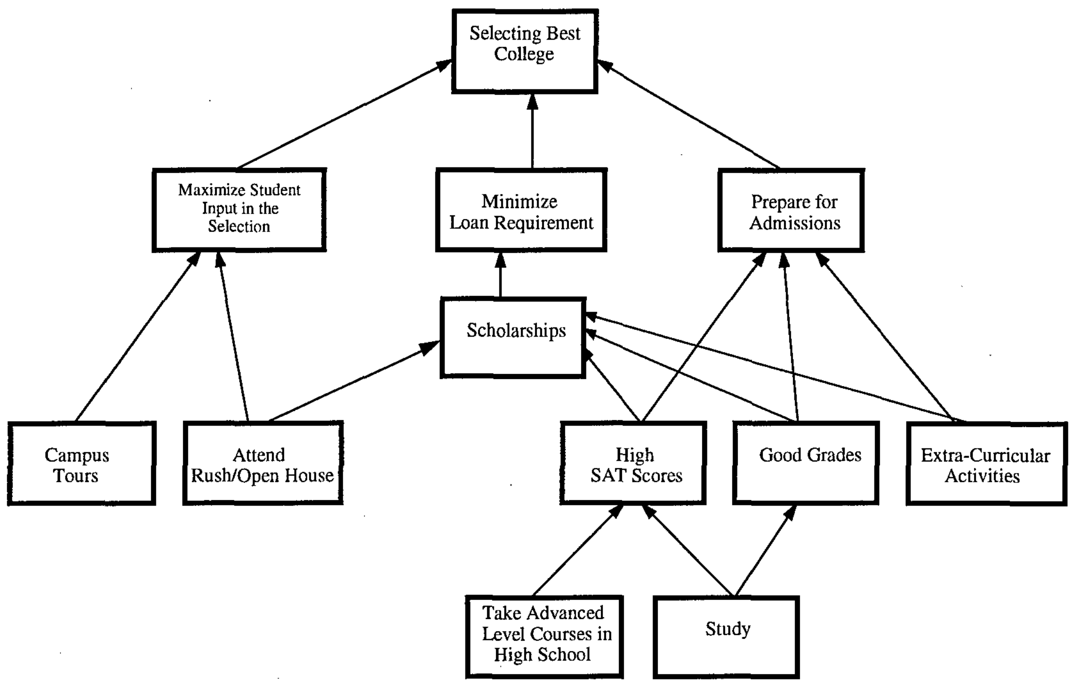


Figure 2.4 Means objectives network for selecting a college.

The strategic objective is still selecting the best college. This is achieved by maximizing the student's input into the selection, minimizing loan requirements, and preparing the student for admissions. The student provides input by taking campus tours and attending rushes and open houses given by the colleges. Scholarships minimize loan requirements. Chances for receiving scholarships are influenced by attending open houses, high SAT scores, good grades, and involvement in extra-curricular activities. In addition to increasing the probability of receiving scholarships, high SAT scores, good grades, and extra-curricular activities also affect whether the student is admitted into the selected college. The student receives high SAT scores and good grades by studying and taking advanced level courses while in high school.

2.4 Multiattribute Preference Theory

As mentioned in Section 2.2, one of the reasons environmental decisions are very difficult is the multiple objectives that a technology strategy must satisfy. Rarely is there an alternative that performs the best on all of the objectives. If such an instance does occur, the decision is easy; choose that alternative! However, these objectives usually compete with each other. For example a technology may do the best job over all of the alternatives in reducing the mobility, toxicity, or volume of a contaminant; however it may be very expensive (thus failing the reduced cost criterion). Since CERCLA states that alternatives must be ranked based on their ability to meet all five balancing criteria (objectives), the decisionmakers must decide the relative importance of each objective with respect to the others.

In addition to deciding the relative importance of the objectives, environmental decisionmakers must compare unrelated objectives. How does one compare reduced human health risk to dollars? Very few decisionmakers could or would tell a group of citizens that a reduction of 'x' in human health risk is worth 'y' dollars! However, the decisionmaker must reduce each objective to similar units to make an "apples-to-apples" comparison of all the alternatives.

Multiattribute evaluation permits simultaneous evaluation of many objectives by quantifying the objectives through a set of evaluation measures, developing weights for each objective, and converting objective evaluation measure scores into common units of measure representing how well an alternative achieves a specific objective. The weights and values associated with each alternative are combined through a function (called an

overall value function). The result is a single overall value representing how well the alternative meets the decisionmakers' strategic objective.

The dimensionless common units of measure are called either a value or a utility, depending if there is uncertainty in the decision variables and/or outcomes. If there is no uncertainty in either the decision variables or the outcomes then the unit is called a value. If there *is* uncertainty in the decision variables and/or outcomes then the unit is called a utility. Since this research performs a *deterministic* analysis of the SDA decision, *values* are used throughout this document.

The remainder of this section is broken into three parts. The first part explains *component* value functions and shows how these single-dimensional functions convert each objective's evaluation measure score into value (worth of an alternative) towards that objective. These functions are called component value functions because they are a *component* of the overall value function. The second part of this section explores how to determine the relative weights associated with each objective. The final part of this section shows how component values and weights for each objective combine, through the use of a multiattribute value function, to calculate an overall value representing how well an alternative meets the decisionmakers' strategic objective.

2.4.1 Criteria Scoring

As mentioned in the previous section, multiattribute preference theory combines an alternative's performance towards evaluation measures into a single value. However, the units associated with the objectives are rarely the same. How does one combine "minimize cost in dollars" and "minimize risk towards human health" into common

units? Placing a monetary value on a life would allow comparisons between the two objectives, but what decisionmaker can say reducing risks to human health to level y is worth x dollars? Another way of combining different objectives is converting an alternative's score towards each evaluation measure into dimensionless units representing how well the alternative meets the decisionmakers objectives. These units are called component values.

Component values are dimensionless units with a fixed range, from a to b, representing the value (to the decisionmakers) of an alternative's evaluation measure score. An alternative providing the worst possible score towards an objective's evaluation measure has value of a for that objective. An alternative providing the best possible score in an objectives evaluation measure has a value of b for that objective.

The literature suggests several methods to determine intermediate component values for alternatives that do not score at either extreme. Perhaps the easiest method is direct assessment, where the decisionmaker uses his or her judgment and experience to provide component values associated with each alternative's evaluation measure. While direct assessment may be easy for the analyst, it requires a lot of subjective judgment for the decisionmaker. It is not uncommon for decisionmakers to be uncomfortable making such direct judgments.

A more common method of assigning component values for criteria evaluation measures is through component value *functions* reflecting how much value a criterion evaluation measure provides throughout its entire range. Imagine an evaluation measure that has its worst possible score at y and its best possible score at z and the value

associated with these extremes are zero and one respectively. Figure 2.5 shows three possible ways to determine the decisionmakers' component value function of such an objective.

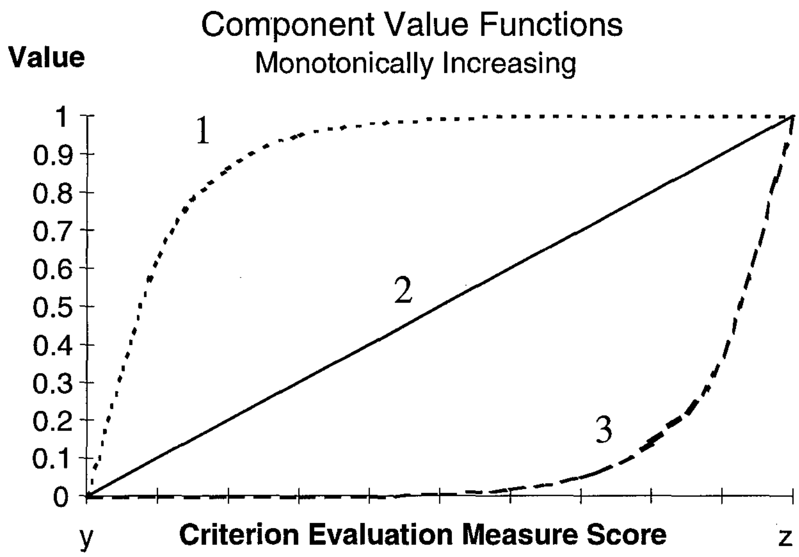


Figure 2.5 Monotonically increasing component value function examples.

Figure 2.5 shows a criterion evaluation measure where the decisionmakers' value towards the objective is *monotonically increasing*; indicating that increasing the evaluation measure always increases (or keeps at the same level) the an alternative's value to the decisionmakers, i.e., percent reduction of site risk to human health. Thus, as evaluation measure score increases from *y* to *z*, the value to the decisionmakers increases from zero to one. The differences between the component value functions show the rate at which increased evaluation measure scores translate into increased value. Component value function "1" shows decisionmakers who believe the value associated with the measure has marginally decreasing rates or return. Component value function "3" shows decisionmakers who believe the value associated with the measure has marginally increasing rates of return. Finally, component value function "2" shows decisionmakers

who feel that the rate of return in value is constant throughout the entire evaluation measure range.

Higher criterion evaluation scores do not always translate into higher component value to the decisionmaker. There are some component value functions that are monotonically *decreasing*, indicating that high criterion measure scores decrease (or keep at the same level) the value to the decisionmaker, i.e., cost.

Figure 2.6 shows a criterion evaluation measure where the decisionmakers' value towards the objective is *monotonically decreasing*. Thus, as the evaluation measure score increases from y' to z', an alternative's value decreases from one to zero. Component value function "1" shows decisionmakers who believe that an alternative provides a lot of value throughout most of the range. However, at some value towards the end of the range, the value rapidly decreases. Component value function "3" shows decisionmakers who feel an alternative's value decreases rapidly as the evaluation measure score moves from the ideal score (y). However, the rate of decreasing value decreases as the evaluation measure score increases. Finally, component value function "2" shows decisionmakers who feel that the rate of decrease in value is constant throughout the entire evaluation measure range.

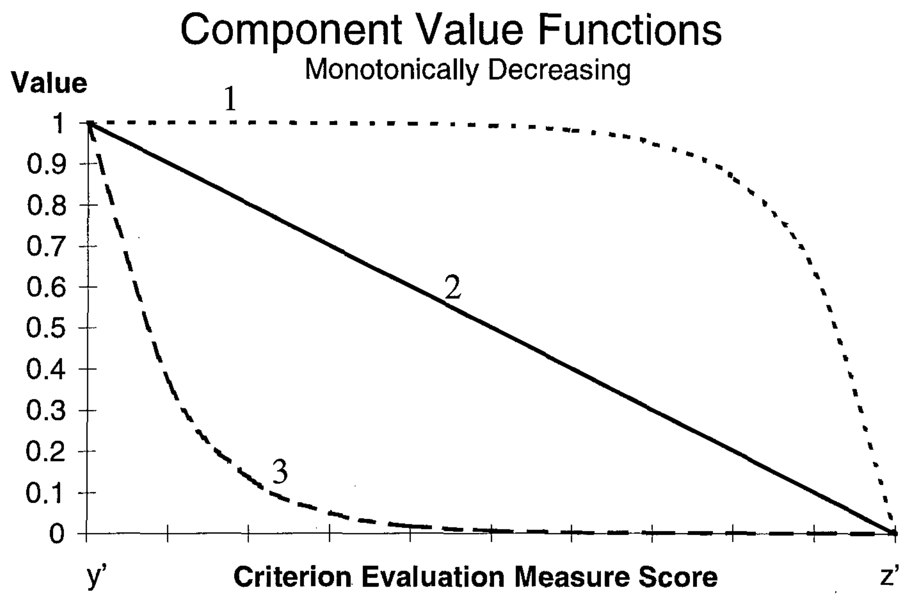


Figure 2.6 Monotonically decreasing component value function examples.

Of course component value functions are not limited to the examples just shown. Any monotonically increasing or monotonically decreasing function is acceptable as long as the function accurately reflects the decisionmakers' attitudes.

2.4.2 Assessing Objective Weights

Objective weights quantify the relative importance of each objective; the more important the objective, the greater the weight. Assigning weights to objectives forces the decisionmaker to determine tradeoffs between objectives. The sum of all of the weights on a particular level of the value hierarchy must equal one (or 100 percent). Therefore, if the decisionmakers feel that an objective should have more weight, then the weight added to that objective must come at the expense of at least one other objective.

If there are n objectives and the decisionmaker feels that all are equally important, then the weight associated with each objective is simply $1/n$. However, decisionmakers often feel that some objectives are more important than others and should have greater

weight. There are several methods of assessing weights in the literature. This section reviews four of the more common methods: direct assessment, pricing out, swing weighting, and analytical hierarchy process (AHP). Each of these methods rely heavily on the views of the decisionmaker.

2.4.2.1 Direct Assessment

Like direct assessment of component value functions described in the previous section, direct assessment of weights requires the decisionmaker to assign weights to each objective based on his or her experience or judgment, organizational policy, or law. Any set of weights is acceptable as long as the sum of all of the weights for each level of the fundamental objectives hierarchy equal one.

While this method is relatively easy on the analyst, it may be very difficult for the decisionmaker. Direct assessment becomes even more difficult when there is more than one decisionmaker, particularly if the decisionmakers have conflicting opinions. While the decisionmakers can try to reach a consensus using direct assessment, other methods described in this section are often a better approach.

2.4.2.2 Pricing Out

Pricing out determines the marginal rate of substitution between one particular evaluation measure (usually monetary) and any other value measure (Clemen, 1996; 547). Simply stated, this method finds the amount the decision maker is willing to pay for an incremental increase in benefit or an incremental decrease of something undesirable. For example, two common objectives in environmental restoration are the cost and the time needed to remediate the site. If some hypothetical decisionmaker is willing to pay a one

million dollars to reduce the remediation time by one year, then the decisionmaker has priced out the objectives.

Pricing out is very useful because it is straightforward and provides a direct tradeoff between objectives. However, pricing out can be a very difficult assessment to make, particularly for attributes where the decisionmaker has little buying or selling experience, i.e., monetary amounts for reduced risk to human health. In addition, pricing out only makes sense when the marginal rate of substitution remains constant over the entire range of possibilities. For example, pricing out the objectives fails if the decisionmaker, from the previous example, decides the value of one less year to remediate increases one hundred thousand dollars every year after two years.

2.4.2.3 Swing Weighting

The swing-weighting approach applies to virtually any weight-assessment situation. This method requires a thought experiment where the decisionmakers compare individual objectives directly by comparing hypothetical alternatives (Clemen, 1996: 547).

The procedure begins by creating a benchmark alternative containing the worst possible outcome for each objective. Clearly such an alternative would be ranked last. The next hypothetical alternative consists of all of the worst outcomes for all but one objective. For this hypothetical alternative the selected objective is "swung" from the worst possible outcome to the best possible outcome. This process is repeated for the remaining n - 1 objectives.

After generating the list of hypothetical alternatives, the decisionmakers rank each hypothetical alternative. The most preferred hypothetical alternative receives a ranking of 1 while the worst, i.e., benchmark, alternative has a ranking of n. Next, the decisionmakers rank the magnitude of preference among the alternatives. The magnitude of preference is quantified through a score between 0 and 100. By definition, the values are 100 and 0 for the first and n^{th} ranked alternatives, respectively. Finally, the weight for each objective is simply the magnitude of preference for that objective divided by the sum of all the preference values.

The swing weighting method may be a good technique when the members setting the weights have different missions or are advocates of a particular alternative. Since swing weighting calculates the weights through a set of hypothetical alternatives, the members are removed from their advocate roles and forced to look at the problem in a more objective way.

While swing weighting may appear to be an ideal approach in the case just presented, it does have a drawback worth noting. The swing weights are sensitive to the value range of the objectives (Jackson, 1996).

2.4.2.4 Analytic Hierarchy Process (AHP)

Another method of determining objective weights is derived from the Analytic Hierarchy Process developed by Thomas Saaty in the early 1970s. Although the method has several shortcomings compared to multiattribute preference theory [see articles by Dyer (1990a, 1990b), Saaty (1990) and Harker and Vargas (1990)] AHP is a popular method used to determine multiattribute weights.

The AHP method of assessing weights involves pairwise comparisons against the objectives. The method begins with the analyst making a $n \times n$ matrix (known as the pairwise comparison matrix) A, where n is the number of objectives (Winston, 1994: 799). The entry in row i and column j of the pairwise comparison matrix, a_{ij}, indicates the relative importance of objective i compared to objective j. The "importance" of each objective is measured on an integer-valued scale ranging from one to nine. A score of one indicates both objectives, i and j, are equally important and a score of nine indicates objective i is absolutely more important than objective j. For consistency, if $a_{ij} = k$, then a_{ji} must equal $1/k$ and $a_{ii} = 1$.

After completing the comparison matrix, the next step is determining the objective weights. If the decisionmaker is perfectly consistent then $a_{ij} = w_i/w_j$. Thus the comparison matrix is an $n \times n$ matrix of weight ratios. The weights are found by determining the non-trivial solution to the equation $A\mathbf{w}^T = n\mathbf{w}^T$.

The AHP procedure requires considerable pairwise comparisons if there are substantial numbers of objectives. Given the limitations of human thinking ability, the decisionmaker is likely to have inconsistent responses in the pairwise comparison procedure (Kirkwood, 1997: 260). The AHP method incorporates slight inconsistencies and approximates the weights by normalizing the columns of the comparison matrix and finding the average across each row. The average of row i is the approximate weight of objective i.

The advantage of AHP is the decisionmakers compare the importance of an objective relative to one and only one other objective at a time. This can be helpful in

situations where the decisionmakers cannot come to a consensus on weights when they are compared against all other weights. When the objectives are compared one at a time, the decisionmakers focus only on that one comparison, rather than trying to factor in other objectives they feel need attention. Such a shift in focus may increase the possibility of consensus among the decisionmakers.

2.4.3 Overall Value Functions

Overall value functions rank order model results in a way that is consistent with the decisionmakers' preferences for those outcomes (Clemen, 1996: 552). There are several overall value functions that rank alternatives based on multiple attributes (or objectives). There are virtually no limits to the form of an overall value function; as long as the function accurately represents the decisionmakers' preferences and views on the relationships between each objective towards obtaining the strategic objective. However, the purpose of decision analysis is to assist decisionmakers in the process of *understanding and constructing their own preferences* (as opposed to an analyst predicting how they might behave). Thus there is benefit to using simplified and easily understood models, coupled with sensitivity analyses, rather than attempt more precise modeling of the decisionmakers preferences (Stewart, 1995; 247).

The more commonly used overall value functions are the multiplicative value function and the additive value function. However, the simplicity of the additive value function is particularly appealing for use in prescriptive decision analysis because the underlying basis is easily understood and allows extensive sensitivity analyses (Stewart,

1995: 252). For this reason, the remainder of this sub section explores the properties of the additive value function.

The additive value function assumes component value functions $v_1(x_1), \ldots, v_n(x_n)$ for n different objectives with evaluation measure scores x_1 through x_n for each alternative. The additive value function also assumes each component value contains values of 0 for the worst evaluation measure score and 1 for the best evaluation method score. Assuming that the components values fall between 0 and 1 may seem limiting because section 2.4.1 stated that the component values could have any range (from a to b). However the component values can be scaled so they are between 0 and 1 using the following equation

$$v'_i(x_i) = \frac{v_i(x_i) - a}{b}, \tag{2.1}$$

where $v'_i(x_i)$ is the *scaled* value associated with objective i, a is the original lower bound on component value, and b is the original upper bound on component value.

Under these assumptions, the additive value function is simply a weighted average of the different value functions expressed as

$$v(x_1, \ldots, x_n) = \sum_{i=1}^{n} \lambda_i \, v'_i(x_i), \tag{2.2}$$

where the weights ($\lambda_1, \ldots, \lambda_n$) are positive and sum to one (Keeney and Raiffa, 1976: 118). After calculating the overall value, the value can be scaled once again so the range once again between a and b. This is accomplished by the following equation,

$$v_i(x_i) = a + b(v'_i(x_i)). \tag{2.3}$$

The additive value function does not contain any interaction terms, implying that the decisionmakers' preferences associated with any one objective are independent of the evaluation measure scores associated with all other objectives. This condition is called preferential independence. For example, if the decisionmaker from the "selecting the best college" example (shown in figure 2.3) prefers lower cost over higher cost, regardless of the level of the aesthetic appearance, then cost is preferentially independent of the good aesthetic appearance criterion.

If preferential independence holds for all possible combinations of the objectives, the objectives are considered mutually preferential independent. Thus, if the same decisionmaker from the above paragraph prefers good aesthetic appearance over poor aesthetic appearance, regardless of the cost, then cost and good aesthetic appearance are mutually preferential independent. If the decisionmakers objectives obey mutual preferential independence then the additive value function properly models their preferences under certainty (Kirkwood, 1997: 239).

2.5 Structuring Decisions

One of the advantages of decision analysis mentioned previously is the ability to structure a complex problem by showing possible courses of action, the possible outcomes, the likelihood of those outcomes, and the eventual consequences possible from those outcomes. Decision analysis structures problems through influence diagrams and decision trees. The following sub sections describe the use of influence diagrams and decision trees and the strengths and weaknesses of both tools.

Several commercial decision analysis software packages use both influence diagrams and decision trees. The user inputs the decision variables and relationships (based on the value-focused thinking methods), the probability data, component value functions, and mathematical relationships. The software then combines this information and applies algorithms to evaluate the alternatives.

2.5.1 Influence Diagrams

An influence diagram uses various geometric shapes to represent different aspects of a decision situation. Rectangles represent decisions, ovals represent chance events, and rectangles with rounded corners represent constant values or mathematical expressions. Finally, arcs between the shapes represent relevance or sequence between two events (ADA, 1995: 194). These geometric shapes (called nodes and arcs) and what they represent are shown below.

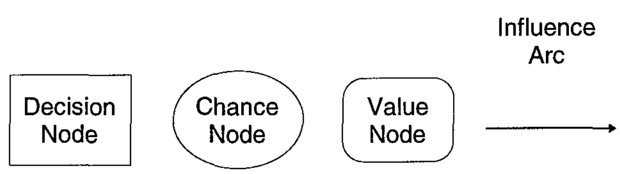


Figure 2.7 Influence diagram elements.

Nodes and arcs are put together in a graph to represent the decision context. To illustrate the use of decision modeling, Marc Blaustein provides a simplified problem based on an actual remediation effort. The decisionmaker must choose among two alternative gas treatment technologies at a Superfund site. The available choices are an incinerator that costs $300 or a flare that costs $120. If the flare is installed, there is a 30 percent chance the flare will be adequate. However, if the flare is not adequate, it will

have to be removed and replaced by an incinerator. The associated costs of requiring an incinerator, after installing a flare, are $390 (Blaustein, 1991: 89).

The resulting influence diagram of this problem facing the decisionmaker is illustrated in the figure below.

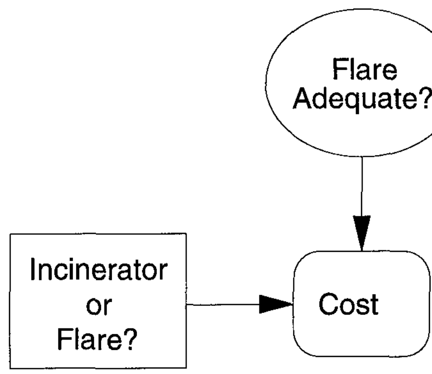


Figure 2.8 Superfund site influence diagram.

This influence diagram clearly shows the decisionmaker is choosing between an incinerator or a flare. The decisionmaker's choice influences the cost of the treatment technology. However in addition to the decisionmaker's selection, the cost is affected by whether or not a flare is adequate. Finally, the fact there is no influence arc from the decision node to the uncertainty node implies the decisionmaker's selection does not affect the probabilities associated with whether or not the flare is adequate.

As this example shows, influence diagrams are very helpful in presenting all of the variables in a complex decision in a clear, concise way. The diagram shows which aspects of the decision influence each other and which variables are uncertain. However, in providing such a simplistic view of the decision, a great deal of detail is not shown. For example, from figure 2.8, one cannot see the probabilities associated with the

adequacy of the flare. If such detail is necessary, then the decision structure should be presented as a decision tree.

2.5.2 Decision Trees

Decision trees display more details of the decision context than influence diagrams. However, providing more details causes the decision trees to exhibit clutter much quicker than influence diagrams. Like influence diagrams, squares represent decisions, while circles represent uncertain events. Branches emerging from the squares and circles represent alternatives to the decisionmaker and possible outcomes of a chance event respectively. The consequence of each decision element and the uncertainty associated with each consequence are represented as a triangle at the end of the branches.

The gas treatment technology problem, shown previously, is structured as a decision tree in the figure below.

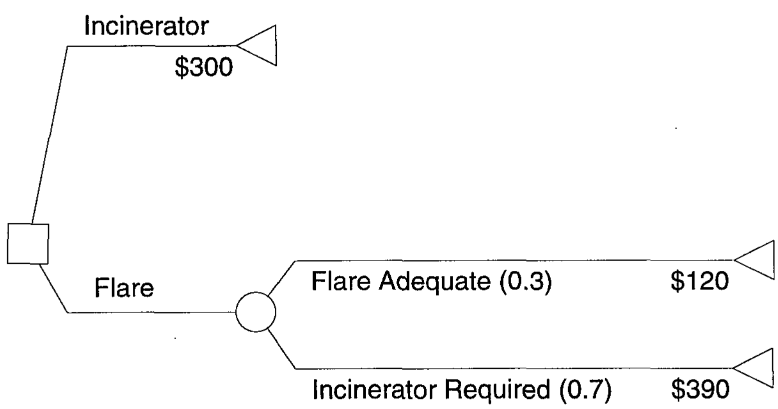


Figure 2.9 Gas treatment technology decision tree (Blaustein, 1991: 89).

This decision tree clearly shows that choosing the incinerator will cost $300. In addition, the decision tree clearly shows that the cost of a flare is $120. However, there is

a 70% chance that the flare will not be adequate. If the flare is not adequate, an incinerator is required at a cost of $390.

The advantage of using decision trees is clear in the above example. The decisionmaker can clearly see the decision structure, the associated probabilities, and the outcomes as they apply to the alternatives. The disadvantage of using decision trees is the fact they can present too much information at once and overwhelm the decisionmaker. This is particularly true in even moderately complex problems.

2.6 Summary

Environmental remediation problems characterized by: uncertainty associated with the waste and the risks involved, several different variables, conflicting objectives, and multiple decisionmakers. The literature indicates that value-focused thinking and multiattribute preference theory, combined with decision analysis techniques, are appropriate methods of evaluating remediation technology strategies for remediation sites. These methods are appropriate because they are designed to address the difficulties associated with environmental remediation problems

Value-focused thinking structures decisionmakers' values into fundamental objectives hierarchies and means-objectives networks. This process encourages the decisionmakers to think about how the alternatives rank with respect to their values rather than ranking the alternatives against each other. Looking at decisions in this matter has several advantages: uncovering hidden objectives, creating new alternatives, identifying decision opportunities, guiding information collection, facilitating involvement with

multiple decisionmakers, improving communication, and providing a structure for evaluating the alternatives.

Decision analysis techniques like multiattribute preference theory and modeling evaluate the alternatives. Multiattribute preference theory assigns weights to the decisionmakers' objectives and converts an alternative's ability to achieve an objective into component value. The weights are found using one of several techniques: direct assessment, pricing out, swing weighting, and AHP. Component values related to objectives are determined using direct assessment or mathematical equations. An additive value function can combine these weights and component values to provide a quantitative measure of an alternative's overall value to the decisionmaker.

Finally decision trees and influence diagrams structure decisions. Influence diagrams present very complex problems clearly, but do not provide many details. Decision trees provide many details of the decision variables and uncertainties. However, providing such detail can overwhelm the decisionmakers and provide little insight to the actual decision structure. Software packages can use decision trees and influence diagrams, along with user inputs from multiattribute preference theory, to evaluate the alternatives.

3. Methodology

3.1 Introduction

Based on an examination of the literature and Idaho National Environmental Engineering Laboratory's Sub-surface Disposal Area, value-focused thinking and multiattribute preference theory were selected as the best methods for creating a deterministic decision analysis model to select a remediation strategy for the SDA site. Applying value-focused thinking ensures the strategies are ranked based on their value to the decisionmakers. Multiattribute preference theory captures the decisionmakers' preferences towards each fundamental objective and provides a method of measuring how well alternatives meet the decisionmakers' objectives.

This chapter begins by explaining the decisionmakers' fundamental objectives and how evaluation measures quantifying the fundamental objectives were gathered. Next, the chapter explains how weights and component value functions for the decisionmakers' values were determined. Finally, the chapter describes how the decisionmakers' objectives and preferences were applied to models that ranked 27 specific remedial strategies (trains) considered for the SDA site.

3.2 Fundamental Objectives Hierarchy

By law, each remediation strategy must be ranked with respect to its ability to meet the nine CERCLA criteria. Two of the criteria, overall protection of human health and the environment and compliance with ARARs, are considered threshold criteria that all strategies must meet. Two more criteria, state acceptance and community acceptance are considered modifying criteria applied after releasing the record of decision to the

public (hence they do not apply to this analysis). Finally, there are five balancing criteria: reduction of toxicity, mobility, or volume through treatment; short-term effectiveness; long-term effectiveness; implementability; and cost. Because the law states that the SDA must meet the CERCLA criteria, CERCLA compliance is the decisionmakers' strategic objective. The five modifying criteria and the two threshold criteria are lower-level fundamental objectives leading to the strategic objective.

The next step was determining the lower level fundamental objectives describing the higher-level fundamental objectives. CERCLA provides guidance for the lower-level fundamental objectives for each of the five balancing criteria. This guidance was previously summarized by the hierarchy shown in figure 1.1. This hierarchy and CERCLA's suggestions were presented to decisionmakers from INEEL, EPA, and Idaho. The decisionmakers felt the CERCLA guidance provided a good foundation to build their fundamental objectives hierarchy. However, they felt some objectives were redundant and others did not provide enough detail. The decisionmakers then eliminated the redundant objectives and split objectives that needed more detail into specific categories.

The remainder of this sub section presents the SDA fundamental objectives hierarchy and provides a brief explanation of the differences between the CERCLA guidance hierarchy and the SDA hierarchy. Complete explanation of the CERCLA guidance and reasons behind changes to the CERCLA guidance hierarchy are provided in Appendix B.

The result of the meeting with the decisionmakers is the fundamental objective hierarchy shown in figure 3.1 (Jines, Jorgensen, and Nearman, 1996). Each rectangle

represents a fundamental objective; the bold rectangles represent the five balancing objectives,[1] and the dashed rectangles are the lowest level objectives (or objective) of the balancing objectives. Each objective with a dashed box has an evaluation measure quantifying how well a strategy meets that criterion. These measures and how they apply to the decision analysis are explained in later section. Finally, the weights associated with each criterion are also shown in figure 3.1. However, the reasons behind the weight values are presented in a later section.

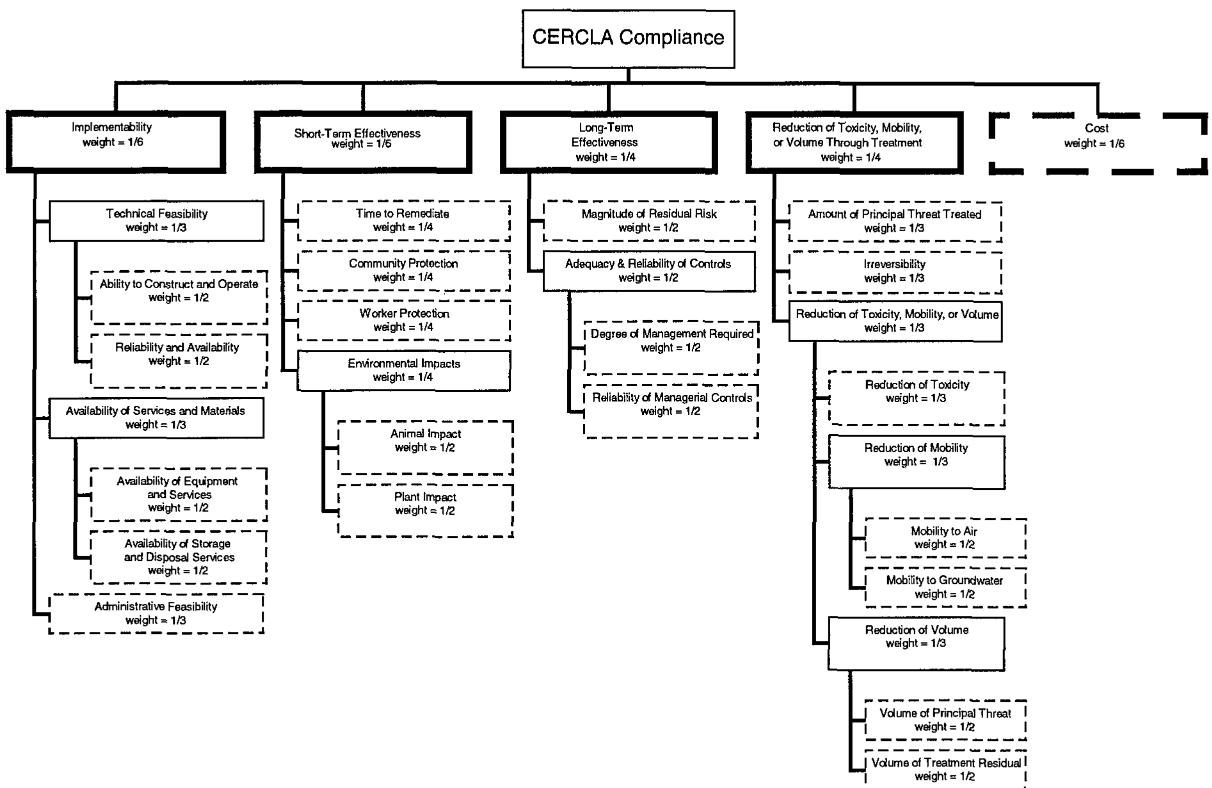


Figure 3.1 SDA fundamental objectives hierarchy.

Clearly the SDA fundamental objectives hierarchy is very similar to the hierarchy suggested by CERCLA. However there are some differences. The following sub sections

[1] This analysis assumes that all of the alternatives meet the threshold criteria. Reasons for this assumption are provided in section 3.6.1.

provide a brief description of the differences between the SDA fundamental objectives hierarchy and the hierarchy suggested by CERCLA. More detailed descriptions are provided in Appendix B.

To keep terminology consistent with CERCLA, top-level fundamental objectives are referred to as CERCLA criteria. Lower-level fundamental objectives are referred to as sub criteria. Sub criteria can be separated into lower level fundamental objectives, called categories. Finally, categories can be further separated into sub categories. For example, the long-term effectiveness *criterion* is explained through two *sub criteria*: magnitude of residual risk and adequacy and reliability of controls. The adequacy and reliability of controls *sub criterion* is further explained by two *categories*: degree of management required and reliability of managerial controls. Finally, if a *category* was explained to yet another level, it would be explained by a *sub category*. However, this is not necessary for the long-term effectiveness criterion.

3.2.1 Implementability CERCLA Criterion

Like the CERCLA guidance hierarchy, the implementability CERCLA criterion in the SDA hierarchy is separated into three sub criteria: technical feasibility, administrative feasibility, and availability of services and materials. However, the decisionmakers felt the technical feasibility and availability of services and materials sub criteria needed more detail.

The decisionmakers provided more detail to the technical feasibility sub criterion by separating it into two categories: ability to construct and operate and reliability and availability. Similarly, the decisionmakers provided more detail to the availability of

services and materials sub criterion by separating it into two categories: availability of equipment and services and availability of storage and disposal services.

3.2.2 Short-Term Effectiveness CERCLA Criterion

Like the CERCLA guidance hierarchy, the short-term effectiveness CERCLA criterion in the SDA hierarchy is separated into four sub criteria: time to remediate, community protection, worker protection, and environmental impacts. However, the decisionmakers felt that environmental impacts needed to distinguish between impacts on plants and impacts on animals. As a result, the environmental impacts sub criterion was separated into two categories: impact on plants and impact on animals.

3.2.3 Long-Term Effectiveness CERCLA Criterion

Like the CERCLA guidance hierarchy, the long-term effectiveness CERCLA criterion in the SDA hierarchy is separated into two sub criteria: magnitude of residual risk and the adequacy and reliability of controls. However, the decisionmakers felt that adequacy and reliability of controls required more detail. As a result, the SDA hierarchy separates the adequacy and reliability of controls sub criterion into two categories: degree of management required and the reliability of managerial controls.

3.2.4 Reduction of Toxicity, Mobility, or Volume Through Treatment

The reduction of toxicity, mobility, or volume through treatment criterion in the SDA hierarchy provides more detail than the CERCLA guidance hierarchy. The decisionmakers felt this detail was necessary because CERCLA states that preference must be given to alternatives meeting this criterion (EPA/540/G-89/004, 1989: 6-8). Furthermore, the decisionmakers felt this preference could only be given to alternatives

that treat the principal threats located on the site. Thus, each criterion in the SDA hierarchy only applies to alternatives treating the principal threats.

Like the CERCLA guidance hierarchy, the reduction of toxicity, mobility, or volume through treatment CERCLA criterion in the SDA hierarchy is separated into three sub criteria: amount of principal threat treated, irreversibility, and reduction of toxicity, mobility, or volume. However, the decisionmakers felt the reduction of toxicity, mobility, or volume sub criterion demanded more detail since it was so important to the CERCLA process. Decisionmakers provided more detail to the sub criterion by dividing the reduction of toxicity, mobility, or volume sub criterion into three categories: reduction of toxicity, reduction of mobility, and reduction of volume.

The CERCLA guidance suggests that reduction of volume category should address two issues, the reduction of volume of the principal threats and minimizing the volume of treatment residuals produced by the remediation process. The decisionmakers incorporated these suggestions by further describing the reduction of volume category through two sub categories: reduction in volume of the principal threat and volume of treatment residuals produced.

Finally, since contaminants are mobile towards two media of concern (air and groundwater), the decisionmakers decided the reduction of mobility category should address both media. Thus, the reduction of mobility category is further defined by the reduction of mobility of the principal threats towards the air medium and the reduction of mobility of principal threats towards the groundwater medium.

3.2.5 Cost

CERCLA recommends separating cost information into three separate sub criteria: capital costs, operations and management costs, and present worth. However these sub criteria can be captured by a single measure, net present value. Net present value combines both capital and operations and management costs occurring over different time periods by discounting future costs to a common base year. The result is a single value representing the amount of money that, if invested in the base year and disbursed as needed, would cover the costs associated with the remediation strategy over its planned life (EPA/540/G-89/004, 1989: 6-12). Thus, the SDA hierarchy does not separate the cost criterion into any lower levels.

3.3 SDA Hierarchy Evaluation Measures

Decisionmakers at the INEEL must evaluate remediation strategies for the SDA by how well they meet the various criteria levels (objectives) described above. A set of evaluation measures specifying how well a strategy meets each criterion is necessary to provide a quantitative ranking of the remediation strategies. Decisionmakers from INEEL, EPA, and Idaho worked with this project's research team and site personnel to provide the set of measures (based on the CERCLA guidance) provided in Table 3.1. Most of the measures need no further explanation. However, measures for community and worker protection and plant and animal impacts use heuristics and qualitative measures outlined in Appendix B. Appendix B also provides the CERCLA guidance and logic used to determine all 21 measures.

Table 3.1 SDA hierarchy evaluation measures.

SDA Criterion	Evaluation Measure
Ability to construct and operate	Number of major system components
Reliability and availability	Percent of major components successfully deployed in similar media
Availability of equipment and services	Number of contractors or subcontractors willing to place bids
Availability of storage and disposal services	Percent of waste that can be stored in known and accepted sites
Administrative feasibility	Number of regulations that apply
Time to remediate	Years before remedial objectives are met
Community protection	Score based on the probability of community exposure risks and magnitude of those exposure risks
Worker protection	Score based on the probability of worker exposure risks and magnitude of those exposure risks
Animal impact	Qualitative ranking based on level of harm imposed on wildlife surrounding the site
Plant impact	Qualitative ranking based on level of harm imposed on plants surrounding the site
Magnitude of residual risk	Risk after remediation divided by the current risk
Degree of management required	Annual long-term management costs
Reliability of managerial controls	Probability of exposure from treated residuals and wastes on-site to human and environmental receptors above protective levels
Amount of principal threats treated	Percent mass of principal threats treated
Irreversibility of treatment	Percent of principal threats in an irreversible form
Reduction of toxicity	Percent reduction of principal threat masses
Reduction of mobility towards air	Percent reduction in principal threat mass flow rates towards air
Reduction of mobility towards groundwater	Percent reduction of principal threat access pathways towards groundwater
Reduction of principal threat volumes	Percent reduction in volume containing principal threats
Volume of treatment residuals	Volume of treatment residuals produced divided by volume of media containing principal threats
Cost	Net present value

3.4 Component Value Functions

Once the decisionmakers were satisfied with the fundamental objectives hierarchy and the evaluation measures quantifying each criterion, the next step was determining the component value functions associated with each of the 21 measures listed in Table 3.1. Component value functions convert an evaluation measure's score into a number representing how much value that score has towards the decisionmakers' objective.

The decisionmakers were presented the methods of determining component value functions described in Chapter Two. However, the decisionmakers did not want to deviate from the guidance provided by CERCLA. Even though CERCLA states whether high or low scores associated with an evaluation measure are preferred, the document does not provide guidance to the shape of the component value function. The decisionmakers felt linear component value functions accurately reflected CERCLA's intentions for most of the evaluation measures. Thus, almost all of the component value functions are linear with either an increasing or decreasing slope.

Component value functions with increasing slopes imply that remediation strategies providing scores at the higher end of the evaluation measure range have higher value to the decisionmaker than strategies providing scores at the lower end of the evaluation measure range. An example of this type of function is the "amount of principle threat treated" evaluation measure. As the percent mass of treated principal threats increases, the value to the decisionmaker increases. Similarly, component value functions with decreasing slopes imply that remediation strategies providing scores at the lower end of the evaluation measure range provide more value to the decisionmaker than strategies providing values at the higher end of the measure range. An example of this type of function is the "volume of treatment residuals" evaluation measure. As the volume of treatment residuals increases, the value to the decisionmakers decreases.

The values associated with each evaluation measure range from 0 to 10. Zero implies the strategy does not provide any value to the decisionmaker for that evaluation measure. Ten implies that the strategy provides the most value to the decisionmaker for

that evaluation measure. The component value functions associated with each evaluation measure and the reasoning behind the form of each function are provided in Appendix B.

3.5 SDA Criteria Hierarchy Weights

The decisionmakers were presented with the weighting methods described in Chapter Two and felt that direct assessment, based on the CERCLA document, best reflected the criterion weights. The weights provided by the decisionmakers were included in Figure 3.1.

The sum of the weights at each level must equal one; recall from Section 2.4.3 that this is a requirement for the additive value function. For example, the five balancing CERCLA criteria weights (implementability (1/6), short-term effectiveness (1/6), long-term effectiveness (1/4), reduction of toxicity, mobility, or volume through treatment (1/4), and cost (1/6)) sum to one (1/6 + 1/6 + 1/4 + 1/4 + 1/6 = 1).

The true weight for any level criterion in the overall value function is the criterion weight multiplied by all of the criterion weights above it. For example, the overall weight of the reliability of managerial controls category under the adequacy and reliability of controls sub criterion of the long-term effectiveness CERCLA criterion is actually 1/16. This is determined by multiplying the category weight (1/2) by the sub criterion weight (1/2) and the CERCLA criterion weight (1/4). Thus, the weight is 1/16 ($1/2 \times 1/2 \times 1/4 = 1/16$).

3.5.1 CERCLA Balancing Criteria Weights

As stated in the previous section, the sum of the weights of the five CERCLA criteria must equal one. CERCLA states there should be "special emphasis on long-term

effectiveness and permanence and reduction of toxicity, mobility, or volume through treatment during the remedy selection (Federal Register, 1990: 8731)." For this reason, the long-term effectiveness and reduction of toxicity, mobility, or volume through treatment criteria were given half of the allowable weight, i.e., the sum of the two criteria weights equal 1/2. Since CERCLA does not state the relative importance of the emphasis given to the two criteria, they received equal weights of 1/4. The remaining weight (1/2) was split evenly among the three remaining criteria since CERCLA does not state that any criterion is more important than the others. Thus the weight associated with short-term effectiveness, implementability, and cost is 1/6 ($1/2 \times 1/3 = 1/6$).

3.5.2 Sub Criteria, Category, and Sub Category Weights

CERCLA guidance does not state any preference towards any of the lower-level objectives. Since CERCLA does not state any preferences, the decisionmakers decided that weights at every level should be divided equally. Thus, if a CERCLA criterion were further described by s sub criteria, then the weight associated with each sub criterion would be $1/s$. This approach was applied to all criteria levels under each CERCLA criterion.

3.6 Decision Analysis Model

After gathering the decisionmakers' objective hierarchy and preferences, the next phase of this analysis was formulating the decisionmakers' values, weights, component value functions, and the overall value function into a decision analysis model implemented in the software packages DPL and Logical Decisions. This model combined the decisionmakers' values and preferences with the data on each criterion

evaluation measure for each strategy considered for the remediation of the SDA. Figure 3.2 outlines the process of how the models operate and interact with a life cycle cost model developed by MSE and EXCEL spreadsheets to assist the decisionmakers in selecting an environmental remediation strategy.

The model translates scores from the best available engineering data (found in Appendix I) and life cycle cost models by MSE (found in Appendix J) for each evaluation measure into value towards a criterion objective. An additive value function combines these component values and weights to provide an overall value representing how well the strategy meets the decisionmakers' values. The greater the value, the more the strategy meets the decisionmakers' values. The models perform deterministic sensitivity analysis on the strategies and rank each strategy based on the worth of that strategy towards the decisionmakers values. The following sub sections list the assumptions used in the decision analysis model and describe how the model captures the decisionmakers' values and preferences.

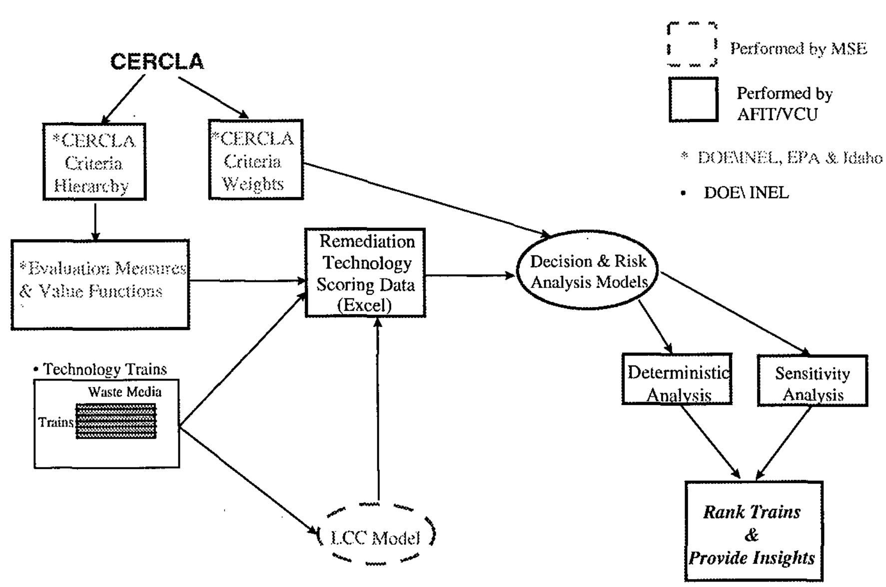


Figure 3.2 INEEL SDA decision analysis model process.

3.6.1 Modeling Assumptions

The decision variables, relationships, and uncertainties associated with determining a remedial strategy at the SDA are very complex and difficult to model. In addition, the decisionmakers at INEEL did not have full data immediately available for many of the criterion measures.

This analysis uses several assumptions to simplify the decision process. The goal of these assumptions is to simplify the decisionmaking process, while keeping enough detail to provide value to the decisionmaker. The assumptions used in this analysis and the reasons behind them are outlined below.

1. **All strategies in the analysis meet the threshold criteria**. This analysis assumes that each strategy meets the overall protection of human health and the environment and the compliance with ARAR criteria. Decisionmakers made this assumption because waivers may be granted towards ARARs (as long as human health and the environment are not threatened) and strategies can be modified to ensure they meet the overall protection to human health and the environment criterion.
2. **All data regarding the wastes on-site is known**. Decisionmakers at INEEL do not know for certain the volume, types, and amounts of the wastes located in the SDA. However, several studies performed on the site provide expected values on these parameters.
3. **Data gathered on strategy performance is known**. This assumption does not accurately reflect the decision context. However, at this stage of the analysis, the best data available for the strategies were expected values and engineering judgment.

Furthermore, it may not be necessary to accurately model the uncertainty associated with all 27 measures for the 28 alternatives, i.e., 567 distributions. Deterministic sensitivity analysis on the technology parameters will determine where uncertainty associated with strategy performance affects the rankings on the top strategies. The decisionmakers can then focus the resources necessary to model the uncertainties associated with those strategies' parameters.

4. **SDA criteria are mutually preferential independent.** This appears to be a reasonable assumption. Great care was taken during the SDA criteria hierarchy process to ensure that the criteria were independent and collectively exhaustive in capturing the decisionmakers' values. This assumption allows the use of the additive value function.

5. **Principal threats are known.** At the time of this analysis, the Baseline Risk Assessment (BRA) that determines the principal threats was not complete. The decisionmakers assumed that the principal threats would be broken into three categories, based on the physical and chemical properties of the principal threats. Category I consists of volatile organic compounds (VOCs): carbon tetrachloride, trichloroethlyene (TCE), and triethylamine (TCA). Category II consists of low level waste (LLW): C^{14}, Tc^{99}, Cs^{137}, I^{129}, U^{234}, U^{235}, and U^{238}. Finally, Category III consists of transuranic (TRU) waste: Pu^{239}, Pu^{240}, and Am^{241}. This analysis further assumes that contaminants within each category behave in the same manner when subjected to treatment processes.

6. **Pits and trenches are remediated in series.** The life cycle cost model (provided by MSE) assumes that the pits and trenches are remediated sequentially, rather than several at a time (Antoniolli, 1997).

3.6.2 Model Development

The decision model for the SDA site consists of four essential elements: the decision, the fundamental objectives hierarchy, the component value functions for each CERCLA criterion evaluation measure, and the decisionmakers' overall value function. Figure 3.3 shows how these elements model the SDA decision.

The selected alternative contains scores associated with each CERCLA criterion evaluation measure (as shown in Table 3.1). The scores are converted into component value to the decisionmakers through the component value functions (provided in Appendix B). Finally, the five CERCLA balancing criteria values and weights are combined through an additive value function representing how well the alternative meets the decisionmakers objectives.

A significant portion of this chapter was already devoted to the SDA fundamental objectives hierarchy (sections 3.2 - 3.5). The remainder of this chapter will provide further details about the other two essential elements to the decision analysis model, the decision and the mathematical relationships.

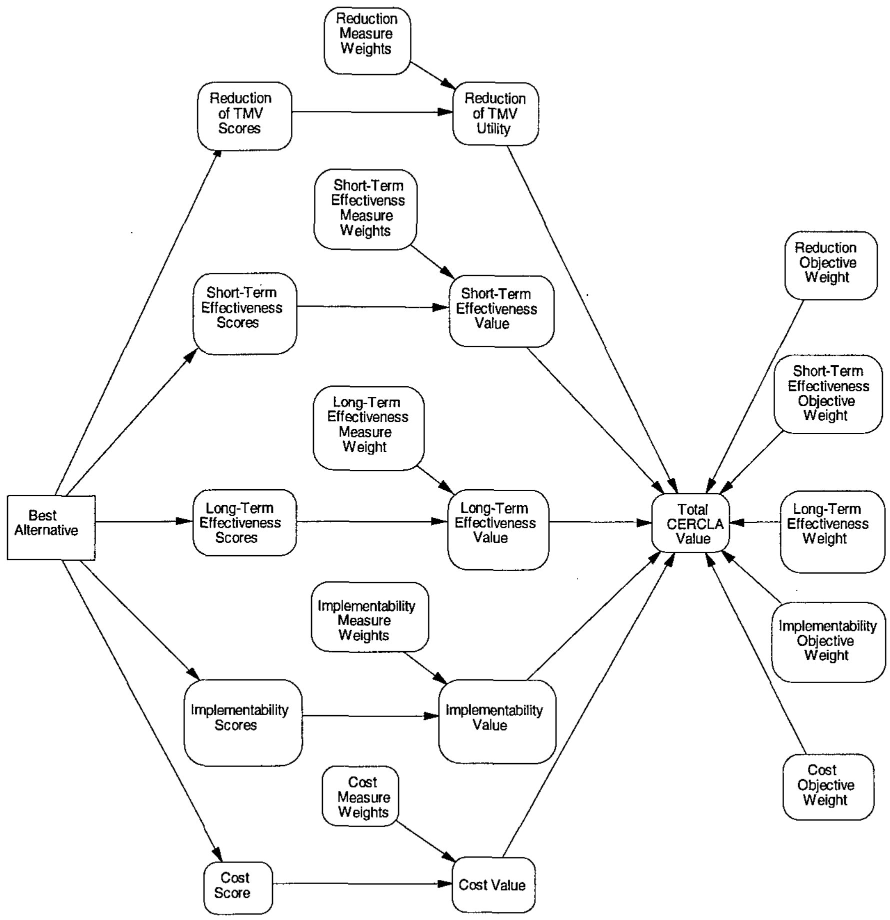


Figure 3.3 Simplified influence diagram of the SDA decision process.

3.7 Development of Remediation Strategies

The SDA decision analysis model contains only one decision, the best alternative. An alternative consists of either a technology, called a process option, or a series of process options called trains. Process options are grouped into categories called general response options. Chapter One listed five general response actions (GRAs) considered as the basis for the remediation strategy at the SDA. Specific technologies within a GRA or combinations of technologies within multiple GRAs form remediation strategies.

The process options considered in this analysis for the SDA site remediation are summarized in Table 3.2. This table is called a strategy generation table. The first row in

the table shows the GRAs mentioned in Chapter One. The columns under each GRA represent the process options being considered either independently, or as part of a train, to remediate the SDA. Appendix H provides a brief description for each process option.

Table 3.2 Strategy generation table of available process options.

No Action	**Institutional Controls**	**Containment**	**Mining**	**In-Situ Treatment**	**Retrieval**	**Ex-Situ Treat/ Stabilization**	**Disposal**
Monitor	**Land Restrictions**	Slurry/Grout Walls	Horizontal Drilling	Soil Vapor Extraction	Gantry Mobile Building	Vitrification	WIPP
	Fencing	Sheet Piling	Conventional	Vitrification	Mining	Incineration	**On-Site**
	Signs	**None**	**None**	Grouting	Remote Excavation	Engineered Vaults	
	None			**None**	**None**	In-Situ Treatments	
						None	

A technology train begins at the left end of the strategy generation table and moves towards the right. As the train moves across the GRAs, the train may increase it's number of process options by as many process options that exist in a GRA. The bolded process options under each GRA represent the technology train currently being applied at the SDA, prior to a concentrated remediation effort.

Obviously, not just any combination of process options creates a feasible alternative. Even if every combination of process options were possible, it would not be very efficient to evaluate the thousands of possible combinations. For these reasons, INEEL decisionmakers selected, based on expert judgment, 27 specific technology trains to evaluate in the decision analysis model. The technology trains are listed in the Table 3.3.

The first three trains are considered basic trains because all of the remaining strategies build upon them. The first train is monitoring only. The second train is institutional controls consisting of monitoring, fencing, markers, and legal access restrictions. The final building train is a surface barrier consisting of institutional controls and a SDA cap. The remaining 25 trains are shared among five types of systems: multiple containment systems, in-situ vitrification (ISV), in-situ grouting (ISG), engineered vaults, and ex-situ treatments (EST). All of these trains contain the monitoring, institutional controls, and cap process options.

Table 3.3 Technology trains evaluated in this analysis.

Train	Category	Process Options
1	Monitoring	Earthen cover, present level of monitoring and maintenance of surface water drainage. (Process option is monitoring)
2		Monitoring, fencing, markers, legal restrictions. (Process option is institutional controls)
3	Multiple Containment	Institutional Controls, cap. (Process option is surface barrier.)
4		Soil vapor extraction, slurry walls, horizontal drill w/ grout, and surface barrier
5		Soil vapor extraction, slurry walls, mining with concrete fill, and surface
6		Soil vapor extraction, slurry walls, and surface barrier
7		Soil vapor extraction, sheet piling, horizontal drill w/ grout, and surface barrier
8		Soil vapor extraction, sheet piling, mining with concrete fill, and surface barrier
9		Soil vapor extraction, sheet piling, and surface barrier
10		Soil vapor extraction, horizontal drill w/ grout, and surface barrier
11		Soil vapor extraction, mining with concrete fill, and surface barrier
12		Soil vapor extraction and surface barrier
13	In-Situ Treatment	*In-situ vitrification and surface barrier*
14	(ISG)	In-situ grouting and surface barrier
15	(ISG & ISV)	In-situ grouting pretreatment, in-situ vitrification, and surface barrier
16	Engineered Vaults	Gantry mobile building, engineered vaults, and surface barrier
17		Mining, engineered vaults, and surface barrier
18		Remote excavator, engineered vaults, and surface barrier
19	Removal , Staging Pit,& In-Situ Treatment	Gantry mobile building, in-situ vitrification, and surface barrier
20	(ISG)	Gantry mobile building, in-situ grouting, and surface barrier
21	(ISV)	Mining, in-situ vitrification, and surface barrier
22	(ISG)	Mining, in-situ grouting, and surface barrier
23	(ISV)	Remote excavators, in-situ vitrification, and surface barrier
24	(ISG)	Remote excavators, in-situ grouting, and surface barrier
25	Removal & Ex-Situ Treatment	Gantry building, chemical pretreatment, plasma furnace, and ship to WIPP
26		Gantry building, segmented gate, plasma furnace, and ship to WIPP
27		Gantry building, plassma furnace, and ship to WIPP (Full vitrification)
28		Gantry building, incinerator, and ash disposal to WIPP)

Note: Train 13 was removed from analysis because in-situ vitrification alone cannot work on the SDA. Some form of pretreatment must be applied.

3.8 Overall Value Function

The final essential component of the SDA model is the overall value function that combines the component value functions for all of the CERCLA criterion evaluation measures into a single value representing an alternative's ability to meet the decisionmakers' strategic objective. Chapter Two showed there are several overall value functions that model decisionmakers' preferences under certainty. However, one of the assumptions of the SDA model is all objectives are mutually preferential independent (Section 3.6.1). This greatly simplifies the problem of choosing an objective function

As mentioned in Chapter Two, mutual preferential independence allows the use of the additive value function (Kirkwood, 1997: 239). Thus, the values and weights associated with each criterion's evaluation measure are combined using the following equation

$$V(X_j) = \sum_{i=1}^{5} \lambda_i v_i(x_j^i), \qquad \textbf{(3.1)}$$

where $V(X_j)$ is the overall value of train *j* with set of evaluation measures scores X_j, λ_i is the weight associated with the *i*th CERCLA balancing criterion, and $v_i(x_j^i)$ is the component value on the *i*th CERCLA balancing criterion provided by train *j* with evaluation measure score x_j^i. Finally, the sum of all of the λ_i's equals one.

Equation 3.1 shows that each of the five balancing criteria has their own additive value functions. These value functions for each CERCLA criterion are in the form provided by eqn. 3.2

$$v_i(x_j^i) = \sum_{k=1}^{n} \lambda_i^k v_i^k(x_j^i) \text{ for } i = 1 \text{ to } 5 \quad \textbf{(3.2)}$$

where n is the number of evaluation measures quantifying the ith balancing criterion, λ_i^k is the weight associated with the kth evaluation measure quantifying the ith balancing criterion, and $v_i^k(x_j^k)$ is train j's value (provided by score x_j^k) towards the kth evaluation measure quantifying the ith balancing criterion. In addition the sum of the λ_i^k's is one. Appendix C provides detailed explanations and sample calculations using the above equations.

It is important to note that in addition to providing the overall value to the decisionmaker, the models also provide the value towards each CERCLA balancing criterion. Providing the values associated with each of the five CERCLA balancing criteria, as well as the overall value, provides decisionmakers more insight to how the trains rank. For example, the decisionmakers will know whether an alternative received a high overall value because each of the five CERCLA objectives were adequately met, or if four of the criteria scored very well at the expense of a fifth criterion.

In addition to providing more information about the how train scores across each criterion, the CERCLA balancing criteria values also provide the decisionmakers insight towards some of the tradeoffs between CERCLA balancing criteria which may occur in the trains. For example, if a series of trains differs by one process option, then the decisionmakers can look at how the values associated with each train differ towards each CERCLA balancing criterion. Differences in CERCLA balancing criterion values can provide insight to tradeoffs between specific process options, i.e., process option A, when

added to this type of train, slightly reduces the value associated with the cost criterion, but greatly increases the value towards the reduction of toxicity, mobility, or volume through treatment criterion.

3.9 Sensitivity Analysis

In addition to providing the nominal overall values associated with each train, the models perform sensitivity analysis to show how sensitive (or insensitive) the nominal result is to changes in model parameters and evaluation measure scores associated with the top ranked train. This analysis uses three methods to perform the sensitivity analysis: sensitivity graphs, tornado diagrams, and rainbow diagrams. A sensitivity graph performs sensitivity analysis on the weights while tornado and rainbow diagrams perform sensitivity analysis on train evaluation measure scores. The following sub sections describe these sensitivity analysis methods.

3.9.1 Sensitivity Graphs

Sensitivity graphs show the effect of changing the weight associated with an evaluation measure or balancing criterion. In each case the overall value associated with each train is calculated as the weight associated with the chosen parameter increases from 0 to 100% of the total available weight. As the value of the chosen weight increases/decreases from its nominal value, the other weights must decrease/increase from their nominal values so the sum of the weights equal one and the relative magnitudes of the weights (weight *a* is two times greater than weight *b)* remain the same throughout the entire range. The final product presents a two dimensional graph showing

the overall value associated with each train across the entire range associated with the chosen weight.

3.9.2 Tornado Diagrams

Tornado diagrams effectively show which evaluation measure scores have the most impact on the overall value associated with the top ranked alternative. A tornado diagram takes evaluation measure scores from one train (usually the top-ranked train) and evaluates the overall value of the top ranked train at three scores entered into the model: a low score, the nominal score, and a high score. All other evaluation measure scores remain at their nominal values. The resulting range in overall value (of the top ranked alternative) from these three scores are plotted on a graph. This process is repeated for all of the evaluation measure scores of interest to the user. Measures causing the greatest changes in overall value are placed on the top while measures causing the least change in overall value are placed towards the bottom. Changes in the top ranked train are indicated by a change in color in the diagram.

A tornado diagram of Blaustein's example problem from Chapter 2 is shown in figure 3.4. The values at either side of the bars show the range and the corresponding change in cost of the better decision respectively. For example, p (probability that the flare is adequate) is varied from 0 to 1. The resulting cost at these values is $120 and $300 respectively. In addition to showing the possible range in values, figure 3.4 shows which variables have the most impact on cost as they vary from the nominal values. Finally, the shaded bars indicate where changes in the optimal decision occur.

Using nominal values, the better decision (assuming the decisionmaker is concerned about expected value) is choosing an incinerator because its expected cost is \$300 and choosing a flare has an expected value of \$309. However, as p increases, (while all other variables remain at their nominal values) the expected cost of choosing a flare decreases. The gray bar associated with variable p indicates that somewhere in p's range (between 0 and 1) choosing the flare is a better decision for the decisionmaker.

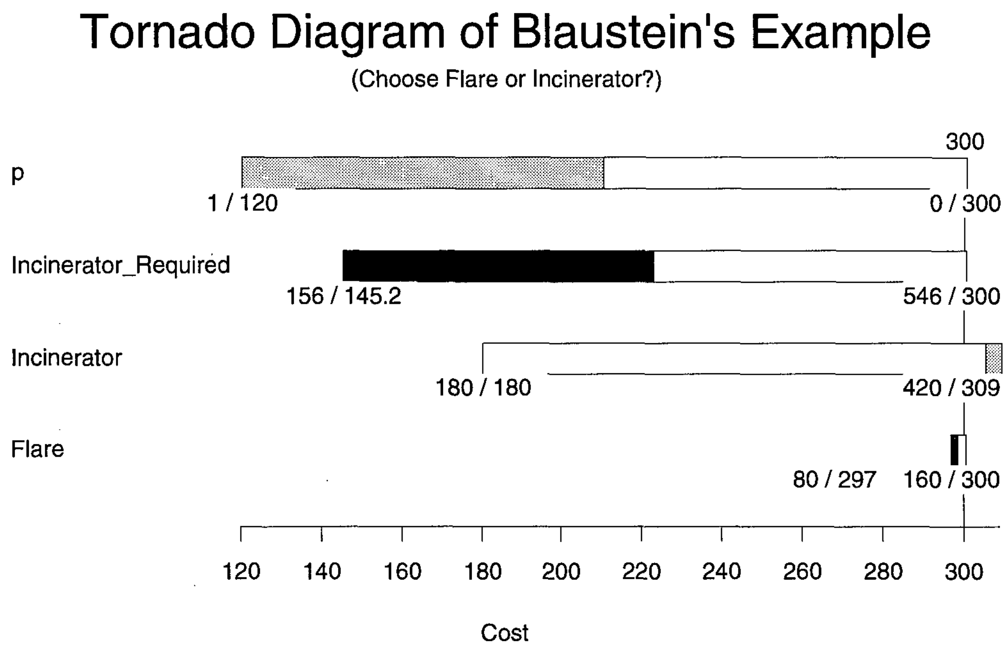


Figure 3.4. Tornado diagram from Blaustein's example from section 2.5.

The tornado diagram effectively of presents the ranges of several variables and the resulting range of consequences (at the extremes) of those variables on the decision. However, the tornado diagram provides no information about the change in cost for points in between the low, nominal, and high values. In addition, the tornado diagram can only show that variables can change the decision somewhere within their range.

However, tornado diagrams do not show at what value the decision actually changes. While such information is not available in tornado diagrams, it is provided in rainbow diagrams discussed in the next sub section.

3.9.3 Rainbow Diagrams

Rainbow diagrams are similar to sensitivity graphs, but apply to evaluation measure scores (rather than weights). Rainbow diagrams show the overall value associated with top ranked alternative through a range of possible values of a selected evaluation measure score (while all other variables remain at their nominal values). In addition to showing how the overall value of the top-ranked alternative varies with the selected evaluation measure score, rainbow diagrams also show where changes in the top-ranked alternative occur within the range. Figure 3.5 shows the rainbow diagram for the variable p (probability that the flare is adequate) in Blaustein's example.

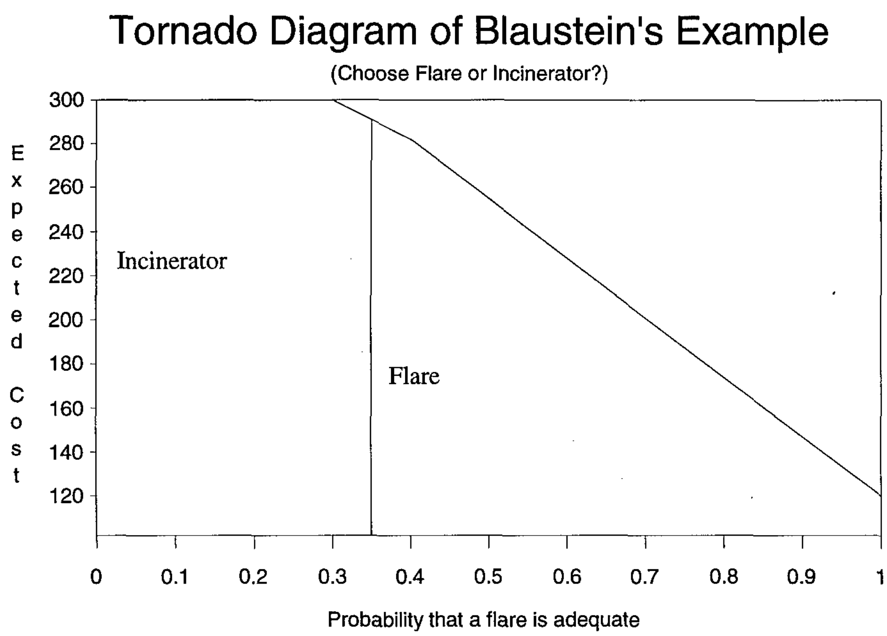


Figure 3.5 Rainbow diagram of the "probability a flare is adequate" variable in Blaustein's example from section 2.5.

Figure 3.5 clearly shows how the expected cost changes as the probability that a flare is adequate increases from 0 to 1. The vertical line between 0.3 and 0.4 indicates that the decision changes when the probability a flare is adequate is around 0.35. This is the point where the expected costs of both decisions are equal. However, as the probability a flare is adequate continues to increase, the expected cost associated with choosing a flare decreases until the probability the flare is adequate is one; resulting in a cost of $120.

3.10 DPL versus Logical Decisions

This analysis uses DPL and Logical Decisions, two different decision analysis software packages, to model the SDA decision. Logical Decisions is a value-focused thinking based software package whereas DPL uses influence diagrams and decision trees. Both software packages have the same inputs and provide the same overall results. However, each software package has its own strengths and weaknesses during the model building and analyzing processes. Table 3.4 shows which model provided better results for a particular modeling or analysis task of this research.

Table 3.4 Logical Decisions (LD) and DPL model strengths and weaknesses.

Modeling Task	**Better ?** LD or DPL	**Reason(s)**
Model building	LD	Value-focused thinking based programming allows user to enter the objectives hierarchy directly. Contains algorithms that assist in determining weights and utility functions. User enters measure scores into "spread-sheet" form in the model or connects model to an EXCEL spreadsheet.
Adding/Modifying trains	LD	Spreadsheet-like format for entering data makes adding and modifying trains easy.
Modifying model parameters	LD	Allows for different preference sets. Each set can have different weights and utility functions that can apply to the model. Thus, different users can easily enter their preferences into the model to analyze results (under their preferences) instantly.
Ability to show decision variables	DPL	Influence diagram shows all of the variables and how they are related. Logical decisions only shows the objectives hierarchy.
Reporting deterministic results	LD	Provides several presentation methods. Ranks and sorts results based on user preferences.
Criteria weight sensitivity analysis	LD	Automatically changes weight values as the chosen criteria's weight changes from 0 to 100% of the total weight. In addition, LD shows the overall utility of all trains as the weights change.
Score sensitivity analysis	DPL	DPL can create tornado and rainbow diagrams on individual train scores. Logical Decisions cannot perform sensitivity analysis on individual train scores.
Potential for further work	DPL	DPL has capability to model decisions under uncertainty and allows for sequential decisions. Logical decisions has limited uncertainty capability and cannot handle sequential decisions.

3.11 Summary

This research uses value-focused thinking techniques described in Chapter 2 to create a quantifiable fundamental objectives hierarchy for the decisionmakers at INEEL. Next, this research applies multiattribute preference theory techniques to develop component value functions and weights for each evaluation measure used to quantify the five balancing CERCLA criteria. Finally, this research creates a decision analysis model, implemented in both Logical Decisions and DPL, using the fundamental objectives hierarchy and decisionmakers preferences. The model provides the nominal overall values and CERCLA balancing criteria values associated with 27 specific remedial trains. In addition, the model performs sensitivity analysis to show how changes to the model parameters and evaluation measure scores affect the top ranked alternative.

4. Analysis of Results

4.1 Introduction

This chapter presents the results from the SDA's deterministic decision analysis model implemented in Logical Decisions and DPL. This chapter first shows the model rankings based on the CERCLA compliance value. The chapter then explains why a class of trains score well (or poorly) in each of the five CERCLA balancing criteria. Finally, the chapter presents results from a deterministic sensitivity analysis on both the model weights and evaluation measure scores to illustrate the sensitivity (or insensitivity) of the top-ranked train to changes in the criteria weights and to provide insight to which variables have the most impact on the overall rankings.

4.2 Train Rankings

Figure 4.1 on the following page presents the ranking of the trains based on the overall value for the strategic objective of CERCLA compliance. The symbols under the "Category" column indicate the primary treatment associated with a train. Table 4.1 below shows the category symbols and the trains they represent.

Table 4.1 Definition of train category symbols.

Symbol	Category Title	Trains	Primary Technology
◆	Basic	1 - 3	No Action
+	MCS	4 - 12	Multiple Containment Systems
■	ISV	15, 19, 21, and 23	In-situ Vitrification
×	Vault	16 - 18	Engineered Vaults
Δ	Grout	14, 20, 22, and 24	In-situ Grouting
□	EST	25 - 28	Ex-situ treatment

In addition to providing the overall value for each train, figure 4.1 qualitatively shows how CERCLA's balancing criteria contribute to a particular train's overall value. The actual values for each balancing criterion are provided in Appendix K. Not all trains contain the five bars. For example, if a train does not treat the waste, then it scored a zero value towards the reduction of toxicity, mobility, or volume through treatment criterion, eliminating that bar.

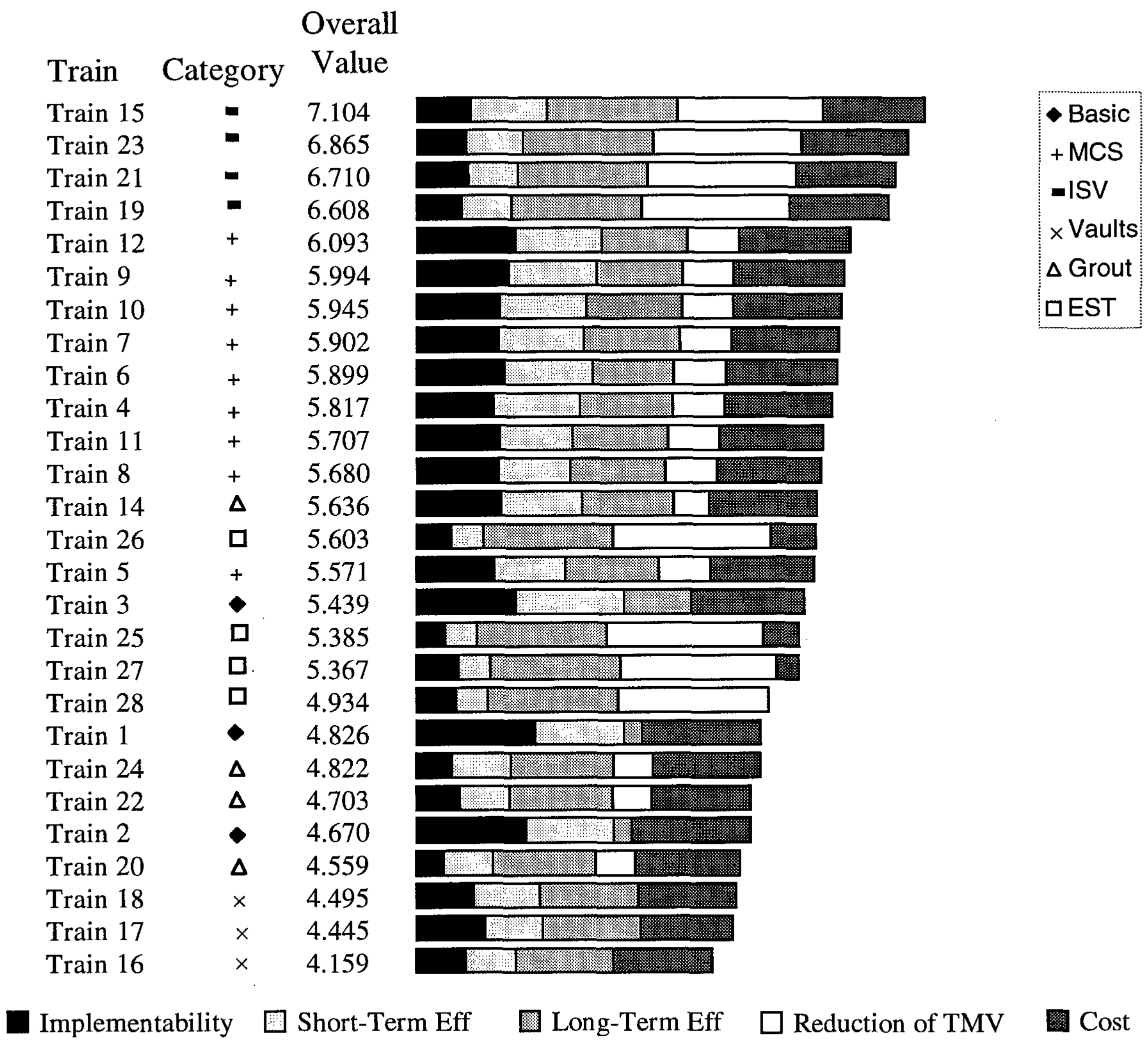


Figure 4.1 Overall value ranking.

Clearly the four in-situ vitrification trains (15, 23, 21, and 19) provide the greatest overall value. The lengths of the five bars to the right of the top four trains show they score relatively well in the long-term effectiveness, reduction of toxicity, mobility, or volume, and cost criteria. However, the lengths of the bars also indicate these trains do not score as well on the short-term effectiveness and implementability criteria as well as some of the other trains.

In addition to qualitatively showing why the top ranked trains score well, figure 4.1 also illustrates why the bottom ranking trains score poorly (overall value < 5). The most common reason for a poor score was a failure to provide any value to the decisionmakers in the reduction of toxicity, mobility, or volume criterion. The 8 trains ranking lowest in overall value had 8 of the 9 lowest value scores associated with the reduction of toxicity, mobility, or volume criterion. These low evaluation results should be expected; CERCLA states that preference should be given to remediation strategies that *do* treat the waste.

Train 28 was the only train with an overall value less than 5 that *does* provide value in the reduction of toxicity, mobility, or volume through treatment criterion. Train 28 scored below 5 because it does not provide any value to the decisionmakers on the cost criterion. Low value in the cost criterion clearly reduced train 28's (as well as the other ex-situ treatments') rankings because their combined value for the other four criteria were similar to the in-situ vitrification train's values without cost. However, in-situ vitrification's higher value towards the cost criterion distinguished it from the ex-situ

treatments. The following sections demonstrate the impact of the lower costs associated with the in-situ vitrification trains.

4.3 Efficiency Frontiers

Figure 4.1 summarizes how individual trains and categories score overall. However, it does not easily show where specific categories of trains perform well or poorly on each of the five CERCLA criteria. Such information can provide insight about the tradeoffs between the 5 criteria that occur between the categories. One way to show how categories of trains perform on each criterion is through scatter plots; diagrams where a train's performance on one criterion is plotted against the train's performance on another criterion. Since trains within a category are likely to perform relatively the same towards each of the five criteria, they should "group together" on a scatter plot.

The following sections provide and interpret scatter plots of the overall value and four of the CERCLA balancing criteria against the cost criterion. The overall value and remaining CERCLA criteria are plotted against cost, not because cost is any more important than the other CERCLA criteria, but because it is quantified through only one evaluation measure, net present value. Thus, the overall value and the remaining criteria are scored against dollars, a familiar common denominator. The cost and component values for the scatter plots are provided in Appendices I and K respectively.

In addition to showing strengths and weaknesses of the categories towards each criterion, these scatter plots show "efficiency frontiers" within each criterion. Efficiency frontiers represent a set of trains that are *not dominated* by any other train with the same cost or value. Saying a train is *not dominated* on a balancing criterion means that for the

cost of that train, no other train provides more value on that criterion than that train. Thus, trains below and to the right of an efficiency frontier are dominated by trains providing more value for the same (or less) cost or by trains costing less and providing the same (or higher) value. Thus, an ideal train is *not dominated* by any other train for each of the balancing criteria. Unfortunately, this is not a likely outcome; there are tradeoffs between the criteria that cause each category to be dominated for at least one criterion. However, clearly seeing which categories are *not dominated* on each criterion aids the decisionmakers in identifying where tradeoffs exist between CERCLA balancing criteria and the categories.

4.3.1 Cost Versus Overall Value

Figure 4.2 shows the net present value (NPV) versus the overall value of each train. For figures 4.2 and 4.3 the overall value refers to the overall value provided by the model *minus* the amount of value contributed by cost. Subtracting the cost prevents "double counting" of the value contributed by cost. The key to the right of the figure shows the markers for each of the categories.

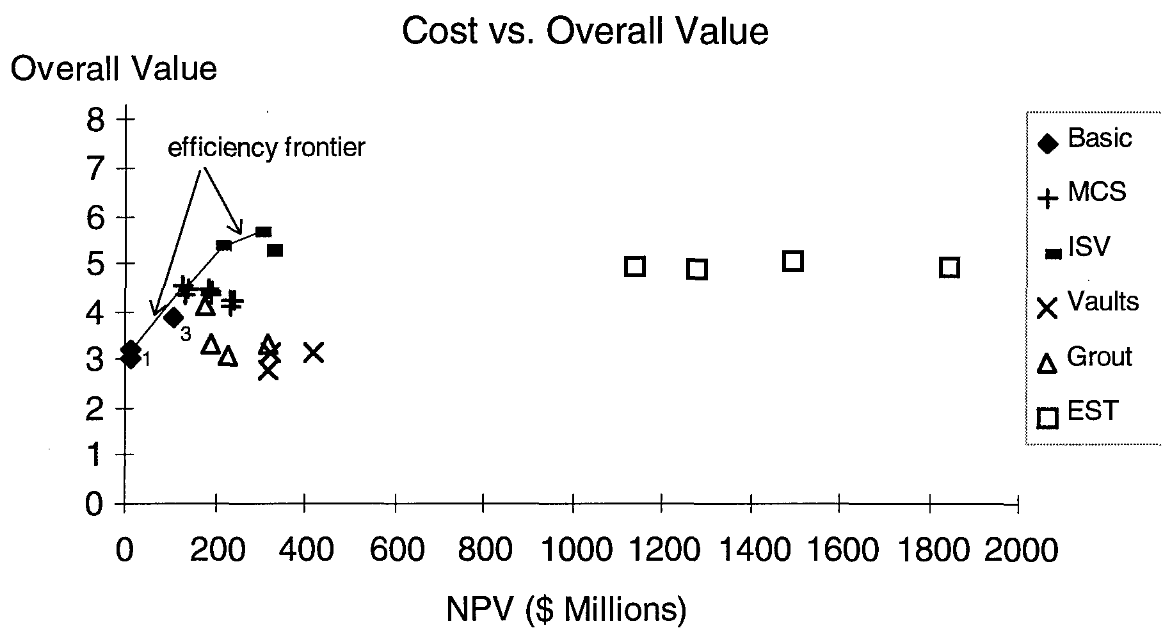


Figure 4.2 Cost versus overall value (minus the value from the cost criterion) scatter plot and efficiency frontier with EST trains.

Like Figure 4.1, the cost versus performance scatter plot shows that the in-situ vitrification technologies have the highest overall value. However, the scatter plot provides additional information about the categories. One can clearly see how well each category of trains performs in both the cost and the overall value. In addition, the magnitude of the costs associated with the ex-situ treatment trains is clear. While the ex-situ treatment trains' overall values are similar to the in-situ vitrification overall values, they have a far greater cost than the in-situ vitrification trains.

The scaling in figure 4.2, required by the magnitude of the costs associated with the ex-situ treatments, cannot show much detail near the efficiency frontier. For this reason, figure 4.3 was developed to provide the same scatter plot without the ex-situ treatment trains.

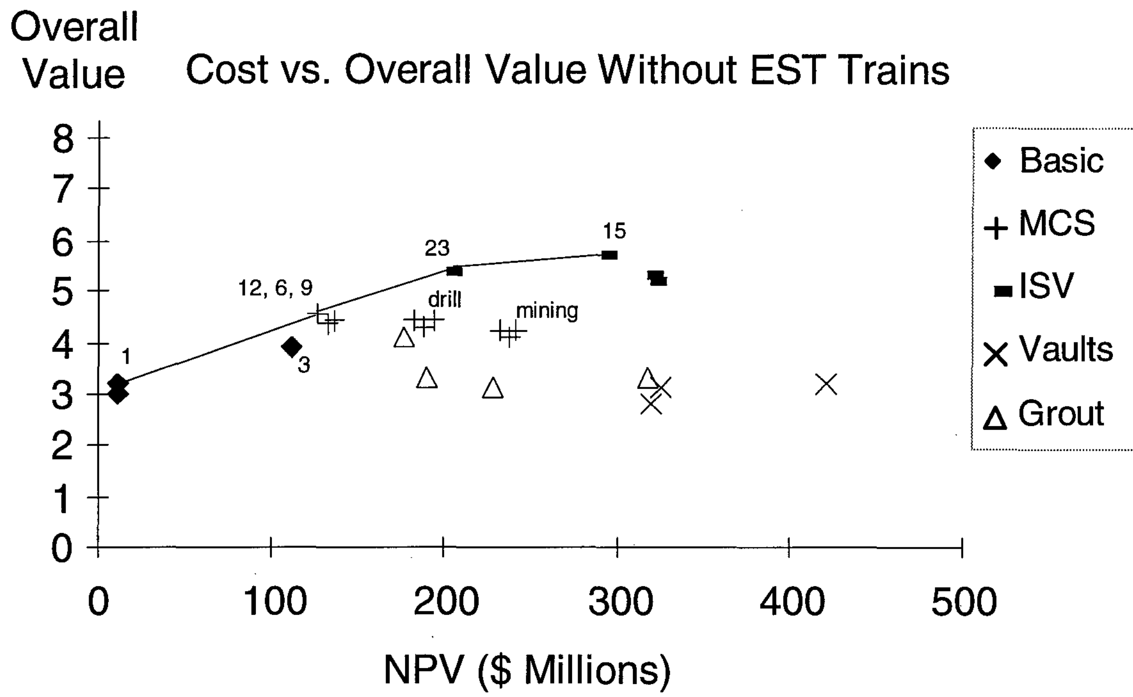


Figure 4.3 Cost versus overall value (minus the value from the cost criterion) scatter plot and efficiency frontier without EST trains.

The line connecting trains 1, 12, 23, and 15 create the efficiency frontier for this analysis. The slope of the efficiency frontier from train 1 to train 12 is approximately the same as the slope from train 12 to train 23. This implies that the "cost" of increased value from train 1 to train 12 is the same as one moves along the efficiency frontier from train 12 to train 23. The slope of the efficiency frontier decreases as one moves from train 23 to train 15. This implies, the "cost" of the additional increase of overall value from train 23 to train 15 is greater than previous increases along the efficiency frontier. It follows then that, although train 15 has the highest overall value, the decisionmakers must decide if the increased value from train 23 to train 15 justifies the additional $88 million dollars.

In addition to the slope of the efficiency frontier, one should notice there are three trains (trains 3, 6, and 9) that are very close to the efficiency frontier. Since the cost values are estimates, it is possible that one of these other trains' costs were overestimated or that train 12's cost was underestimated. If either case is true, there might be a change in the efficiency frontier.

Figure 4.3 does an excellent job of distinguishing the three classes of multiple containment strategies: horizontal drilling, conventional mining, and neither drilling nor conventional mining. While all three multiple containment system classes have nearly the same performance scores, the costs associated with each class distinguishes the trains from each other. Figure 4.3 clearly shows that currently proposed drilling and conventional mining technologies cost between 50 - 100 million dollars more than not drilling and mining and provide no additional performance towards CERCLA compliance. Thus, it appears that horizontal drilling with fractional basalt grouting and conventional mining with concrete backfill are not efficient (dominated) process options to add to the multiple containment system trains.

The cost versus overall value scatter plots effectively present how each category performs overall. However, these figures do not show the tradeoffs of the five CERCLA criteria that occur between the categories, i.e. some categories perform well on some criterion *a* at the sacrifice of some other criterion *b*. These tradeoffs become clear when plotting the remaining four CERCLA criteria (implementability, short-term effectiveness, long-term effectiveness, and reduction of toxicity, mobility, or volume through treatment) against cost.

4.3.2 Cost Versus Implementability

Figures 4.4 (with EST trains) and 4.5 (without EST trains) show scatter plots of the cost versus the implementability criterion. The efficiency frontier for this scatter plot consists of train 1 only. Train 1 dominates all other trains because it is least costly and easiest to implement. While the fact that train 1 dominates all the other trains in this figure should not be very surprising, the figures still are useful in showing the relative difficulty associated with implementing the categories. The basic and multiple containment systems trains are relatively easy to implement; while the vaults, in-situ grouting and vitrification, and EST categories are more difficult to implement.

There is one exception to the above generalization. One of the grouting trains (train 14) has about the same value in the implementability criterion as the multiple containment systems category. The reason for this exception is the fact that train 14 does *not* excavate the waste prior to grouting; whereas the other grouting technologies first excavate, then grout the waste. The addition of an excavation process option to an in-situ grouting train renders the train more costly and more difficult to implement. However as a later scatter plot shows, the excavation process helps improve the grouting results; translating to higher value in a different balancing criterion.

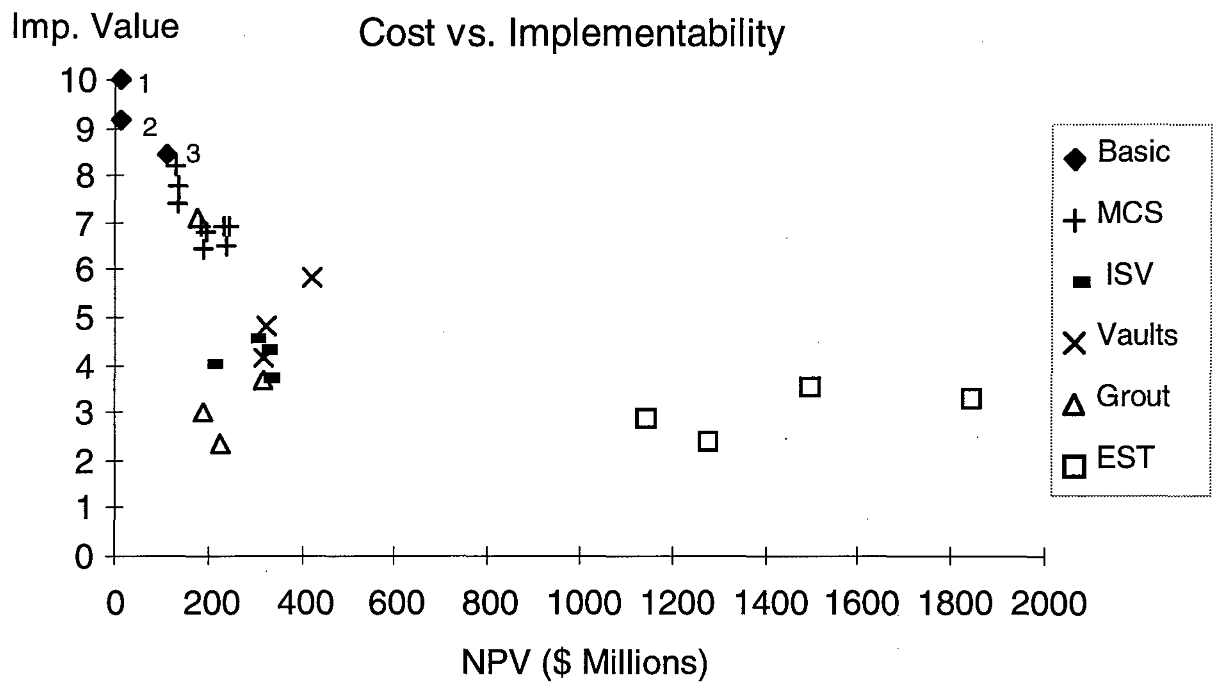


Figure 4.4 Cost versus implementability scatter plot with EST trains.

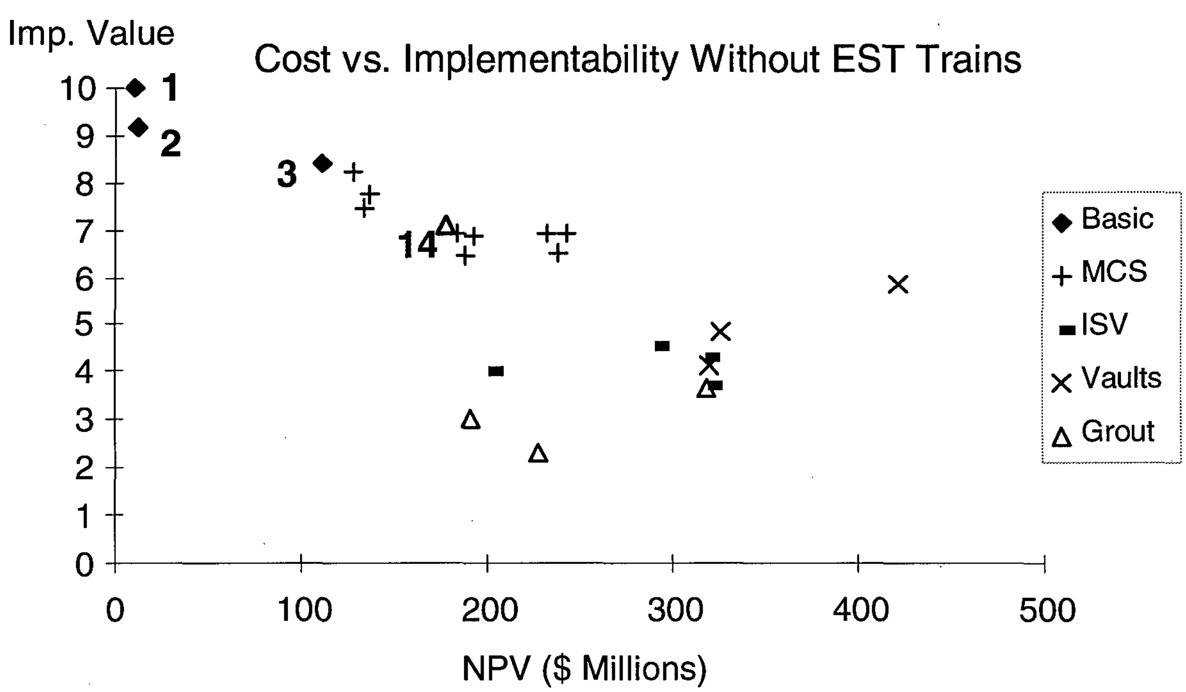


Figure 4.5 Cost versus implementability scatter plot without EST trains.

4.3.3 Cost Versus Short-Term Effectiveness

Figures 4.6 (with EST trains) and 4.7 (without EST trains) show cost versus short-term effectiveness scatter plots. As in the cost versus implementability scatter plots, the Basic category trains make the efficiency frontier. This indicates that any direct interaction with the waste during the remediation process not only increases the cost and time to remediate the site, but it also increases risks to the surrounding community and to workers.

In general, doing nothing to the waste directly provides the most value towards the short-term effectiveness criterion while removing the waste from the SDA provides the least contribution to short-term effectiveness. Consequently, traditional in-situ treatments (trains 14 and 15) provide higher short-term effectiveness value than the other trains in the same categories (first excavate then treat in-situ).

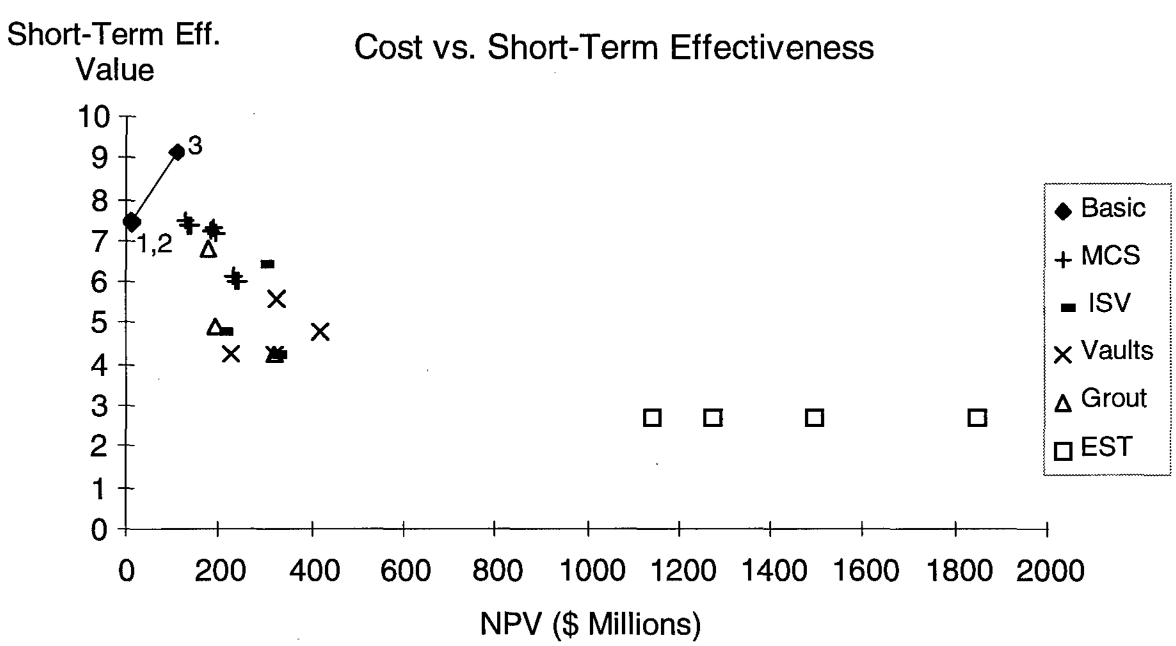


Figure 4.6 Cost versus short-term effectiveness scatter plot and efficiency frontier with EST trains.

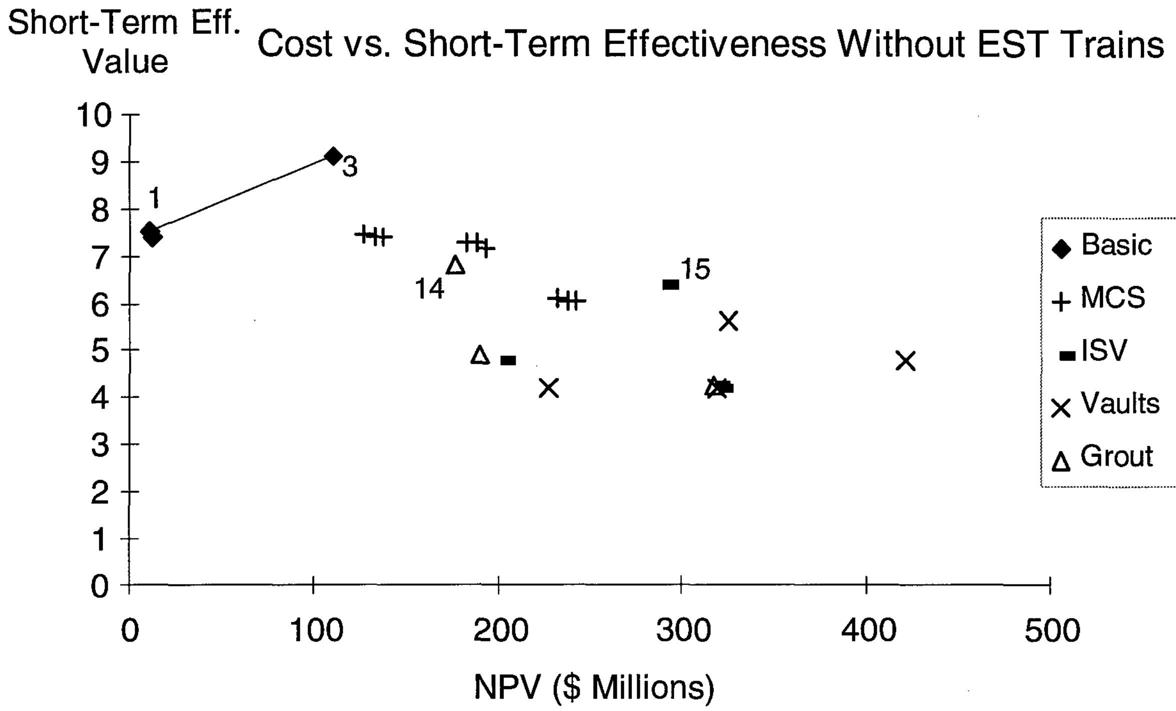


Figure 4.7 Cost versus short-term effectiveness scatter plot and efficiency frontier without EST trains.

4.3.4 Cost Versus Long-Term Effectiveness

Figures 4.8 and 4.9 show the cost versus the long-term effectiveness scatter plots. Like the overall performance scatter plots, the efficiency frontier consists of trains 1, 12, and 23. In addition, the slope of the efficiency frontier is fairly constant as one moves from train 1 to train 12 to train 23. Thus, the rate of increase in long-term effectiveness value remains the same for similar increases in cost along the frontier.

Like the overall performance efficiency frontier, the long-term effectiveness criterion has several trains close to the efficiency frontier. In fact, the trains are the same in both the overall and long term analysis (trains 3, 6, and 9). Since the net present values are only estimates, some of these technologies could change the efficiency frontier (if more accurate cost forecasts change the net present value results). These scatter plots are

also similar to the overall value versus cost scatter plots in that both the in-situ vitrification trains and ex-situ treatment trains score well. However, the trains in the ISV category are less expensive than the trains in the EST category.

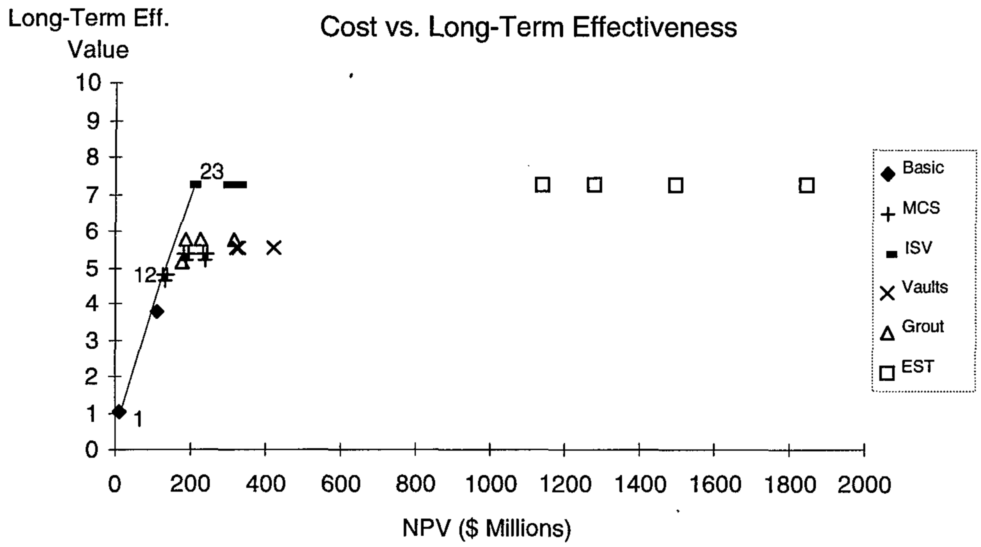


Figure 4.8 Cost versus long-term effectiveness scatter plot and efficiency frontier with EST trains.

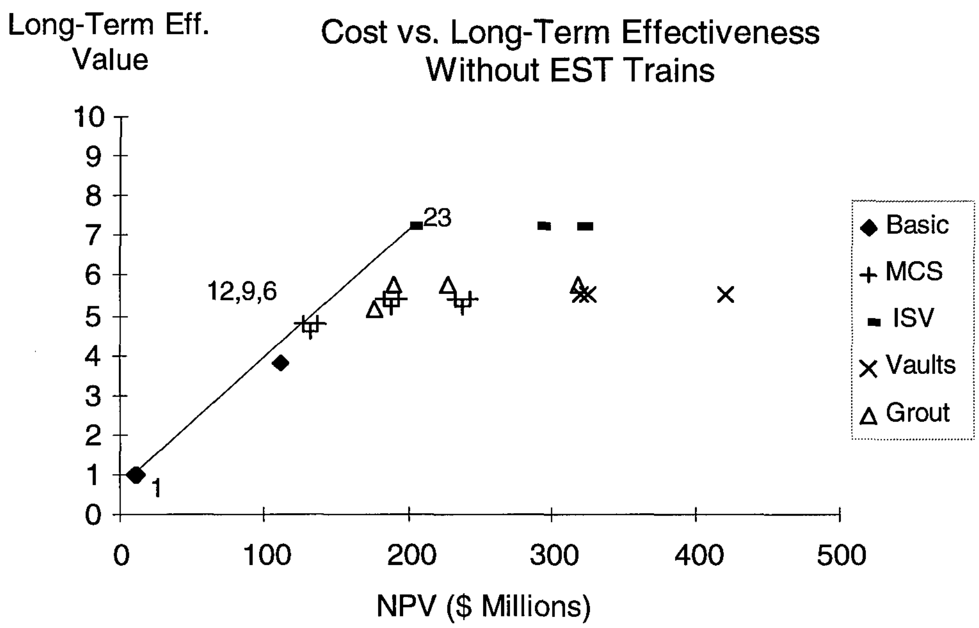


Figure 4.9 Cost versus long-term effectiveness scatter plot and efficiency frontier without EST Trains.

One should note that the technologies that perform well towards the previous two criteria (implementability and short-term effectiveness) do not perform well towards the long-term effectiveness criterion. Thus trains not treating the wastes, while scoring well on the implementability and short-term effectiveness criteria, are much less effective at meeting the long-term effectiveness criterion. This occurs because the wastes remain untreated and continue to pose a long-term threat to the surrounding community. Clearly long-term effectiveness is a tradeoff between implementability, short-term effectiveness, and cost.

4.3.5 Cost vs. Reduction of Toxicity, Mobility, or Volume Through Treatment

Figures 4.10 and 4.11 show the cost versus the reduction of toxicity, mobility, or volume through treatment scatter plots. Like the long-term effectiveness versus cost scatter plots, the technologies that score well towards the reduction of toxicity, mobility, or volume through treatment criterion do not score well on the implementability and short-term effectiveness criteria. Thus trains that treat the waste, do so at the expense of implementability and short-term effectiveness.

Figure 4.10 clearly shows the distinction between the in-situ vitrification trains and the other categories. The in-situ vitrification trains cost about the same as the multiple containment and grouting trains, yet the in-situ vitrification trains provide 3 to 4 times more value on the CERCLA criterion for reduction of toxicity, mobility, or volume through treatment. In addition, the in-situ vitrification technologies have almost the same value as the ex-situ treatments but cost much less.

Measured against the two criteria that make half of the total weight (reduction of toxicity, mobility, or volume and long-term effectiveness), these in-situ vitrification trains provide far more value for the same price as the *non*-EST trains and provide the same value for much less cost than the EST trains. It is clear why trains 23, 15, 21, and 19 score very well overall.

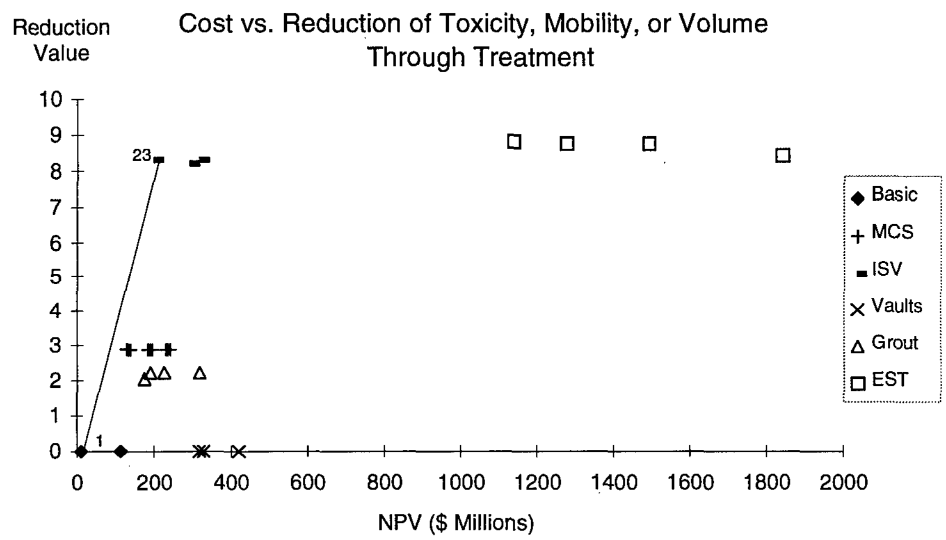


Figure 4.10 Cost versus reduction of toxicity, mobility, or volume through treatment scatter plot and efficiency frontier with EST trains.

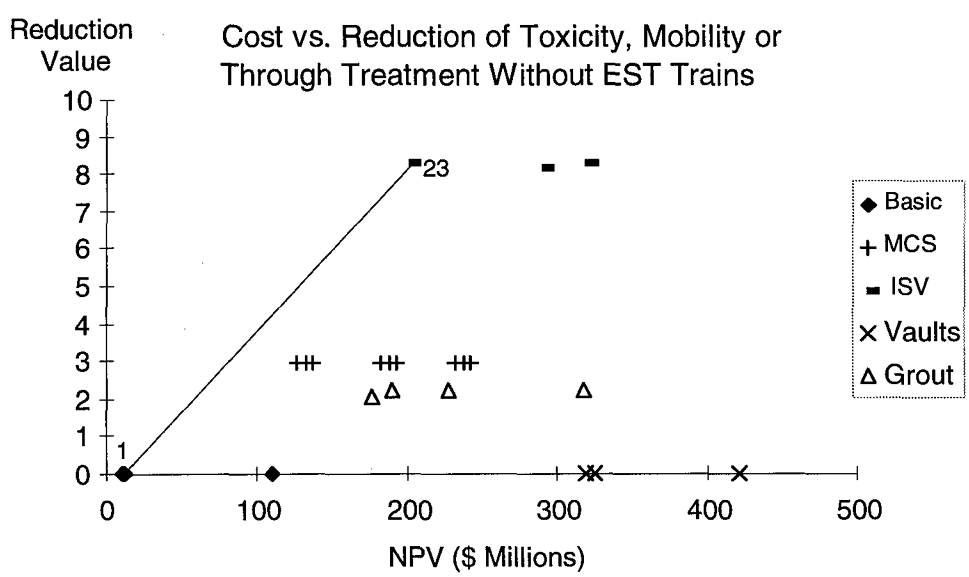


Figure 4.11 Cost versus reduction of toxicity, mobility, or volume through treatment scatter plot and efficiency frontier without EST trains.

4.4 Weight Sensitivity Analysis

Table 4.2 shows how insensitive the top ranked train (train 15) is to changes in the nominal values of the weights given to the five CERCLA criteria. The table summarizes results from a series of sensitivity graphs provided in Appendix L. The sensitivity graphs present each train's overall value as the nominal weight of a specific criterion ranges from 0 to 100% of the overall weight. The first column lists the five balancing criteria. The second column shows the nominal weights (as a percent of the total) associated with each of the balancing criteria. As the weight percentage of the selected criterion increases, the weights associated with the other criteria decrease proportionally. Changes in the criteria weights change the overall value for each train; possibly changing the rankings. Column 3 of the table shows the range where train 15 remains the top-ranked train. Finally, column 4 shows the train that replaces train 15 when the weight percent of a criterion goes beyond the range provided in column 3.

Table 4.2 Summary of weight sensitivity analysis.

Criterion	Current % of Total Weight	Range Where Train 15 is Ranked First	Train Replacing 15
implementability	16.7	0 - 35	12
short-term effectiveness	16.7	0 - 50	12
long-term effectiveness	25	0 - 100	N/A
reduction of toxicity, mobility, or volume	25	7 - 75	12 (low end) 23 (high end)
cost	16.7	0 - 45	23

Table 4.2 clearly shows that the weights associated with each criterion change significantly from their nominal values before train 15 is removed from the top ranking. The table also shows that trains 12 and 23 are the only trains that replace train 15. Train 12 (soil vapor extraction and cap) is ranked 5th overall when using nominal values. Train

23 (remote excavation, in-situ vitrification, and cap) is another in-situ vitrification train ranked 2nd in overall value when using nominal values.

4.5 Score Sensitivity Analysis

This section shows how sensitive or insensitive train 15 (in-situ grouting and in-situ vitrification *without* excavation) is to the 21 measures quantifying the CERCLA criteria. This analysis could, of course, be developed for any of the trains; however, train 15 has the highest nominal overall value. Variations in train 15's scores are likely to have the most affect on the overall value associated with the top ranked train.

Table 4.3 on the following page shows the criteria and the ranges of the evaluation measure scores associated with the criteria used in train 15's score sensitivity analysis. The value range for each measure is +/- 40% of the nominal value. Forty percent was chosen because MSE believes that the actual cost should be within that range (Antonioli, 1997). The +/- 40% range was extended to the remaining evaluation measure scores because train 15 does not excavate the waste prior to the in-situ vitrification treatment. GEOSAFE, the only company providing in-situ vitrification, states that in-situ vitrification's performance can vary in the SDA media (because of the high fraction of void space due to barrels still intact) if the waste is not first excavated and sorted (Hansen, 1997). GEOSAFE did not provide a percentage of the performance variation so this analysis assumed that 40% would be a conservative, i.e. high, estimate.

Table 4.3 Low, nominal, and high scores used in train 15's tornado diagram.

Criterion	Low Score	Nominal Score	High Score
Time to remediate	9	15	21
Community protection	3.6	6	8.4
Worker protection	3.8	6.4	9
Magnitude of residual risk	0	0.1	0.14
Degree of management required	235.8	393	550.2
Reliability of managerial controls	0.01	0.1	0.14
Amount of principal threat treated	51	85	119
Irreversibility of treatment	51	85	119
Reduction of toxicity	45	75	105
Reduction of mobility towards air	54	90	126
Reduction of mobility towards groundwater	59	99	139
Reduction of principal threat volume	12	20	28
Volume of treatment residuals	0.01	0.02	0.03
Cost	76,224	127,040	177,856

Note that not all 21 criteria were used in the diagram because evaluation measures associated with criteria cannot change, i.e. the number of major system components (for the ability to construct criterion). While the values for the community and worker protection measures cannot change with the given heuristic, the scores were used in the sensitivity analysis to see if results from a thorough risk analysis could change the decision.

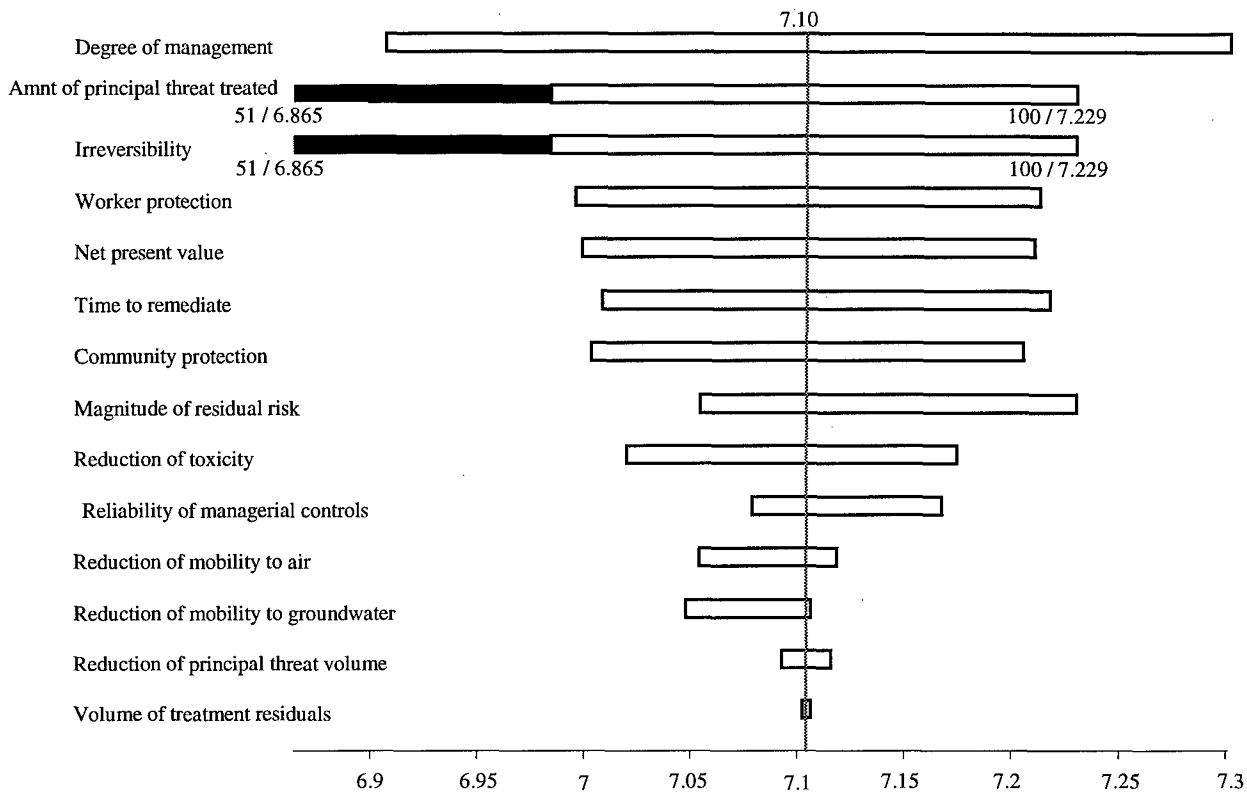


Figure 4.12 Tornado diagram for train 15 measure scores.

The two numbers at either side of the graph for the amount of principal threats and the irreversibility criteria represent the actual score entered and the resulting contribution to overall value respectively. Thus the measure for irreversibility was evaluated at 51 and 100 (percent of principal threats in an irreversible form). The resulting value of the top-ranked alternative at these values were 6.865 and 7.229 respectively. The vertical line labeled 7.104 represents the nominal value associated with the top ranked train (train 15).

The shaded bars associated with the amount of principal threats treated and the irreversibility evaluation measures indicate a change in the top ranked alternative somewhere in the range. Further analysis, through rainbow diagrams provided in Figures

4.13 and 4.14, show that the actual change in ranking occurs when either value is at 56 percent. Thus if updated performance data for train 15 shows that either (or both) of the percent of principal threats treated or percent of waste in an irreversible form perform at a rate below 56 of the principal threats (while all other evaluation measure scores remain the same), then train 23 (remote excavation, in-situ vitrification, and cap) becomes the top-ranked train. Such an event is not impossible. Recall that if the SDA waste media is not excavated prior to in-situ vitrification, the performance results may vary. However, if the waste is excavated then the results are fairly uniform. Thus, it is possible for the performance scores associated with train 15 to vary while the performance scores associated with train 23 to remain relatively the same even though both trains are members of the "ISV" category.

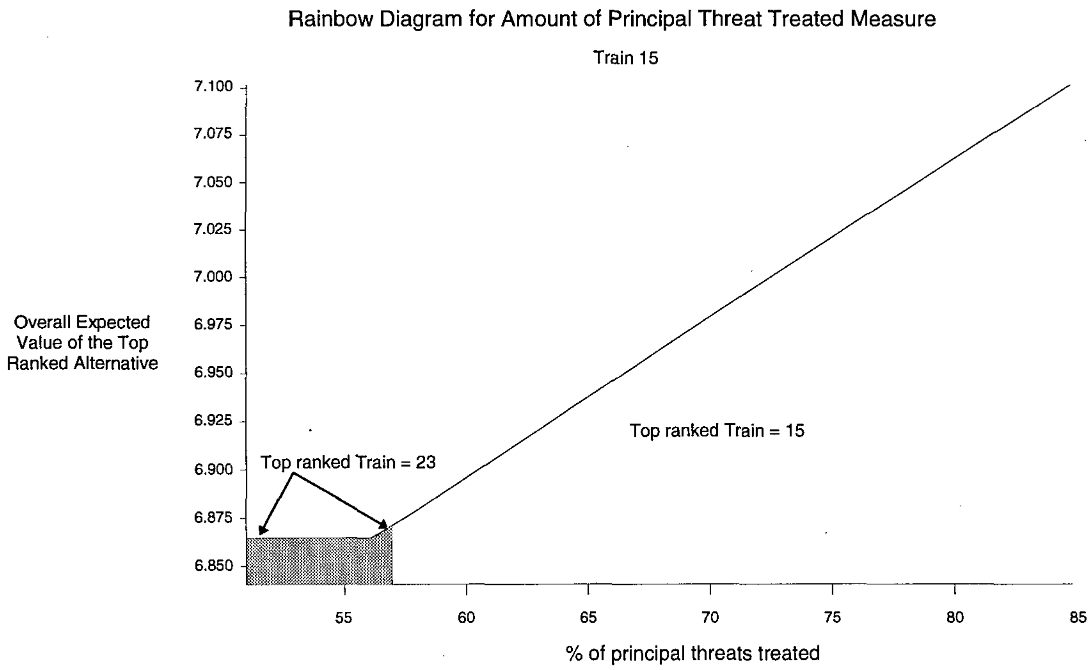


Figure 4.13 Rainbow diagram for train 15's amount of principal threats treated score.

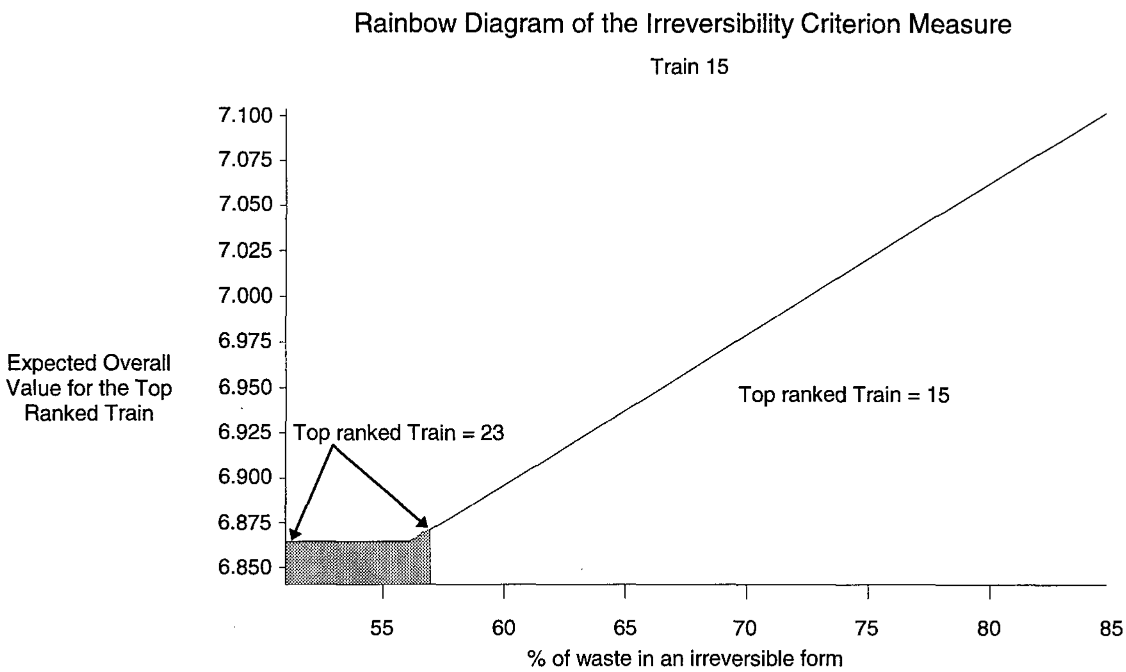


Figure 4.14 Rainbow diagram for train 15's irreversibility measure score.

4.6 Summary

Overall, the decision analysis model provides many tools for analyzing each of the 27 trains. Not only can the model evaluate individual trains, but it also evaluate categories of trains to find the tradeoffs between technologies and the five CERCLA balancing criteria.

The model is an effective aid to the decisionmakers because it does not just give the overall value associated with each train. In addition to the overall value, the model presents the value for each of the five CERCLA balancing criteria. Thus, the decision-makers can determine whether a train scores well because it performed relatively well in all categories or if it performed well towards four of the criteria, but poorly in one.

In addition to clearly showing how each CERCLA criterion contributes to the overall value, the CERCLA criteria values allow the use of scatter plots and efficiency frontiers. The scatter plots illustrate the tradeoffs between particular categories of trains and the CERCLA criteria, while efficiency frontiers provide insight to the technologies that are not dominated by any other technology in that criterion.

For the most part, the scatter plots show that the technologies costing the least are also the easiest to implement and provide the most short-term effectiveness value. This generally occurs because these technologies do not directly treat the waste. Because the waste is never handled directly, there is little (if any) immediate hazard to workers or the community and minimal equipment is necessary.

While not handling the waste directly significantly reduces costs and risks to workers and the community, it does nothing to reduce the toxicity, mobility, or volume of the waste or produce a long-term solution to the problem. These are considerable drawbacks because reduction of toxicity, mobility, or volume and long-term effectiveness are half of the total weight given to the five criteria.

The scatter plots also show that treating the waste, while performing well on the two most important criteria, does have drawbacks of its own. Treating the waste requires handling the waste directly in some way, increasing the risks to workers and the community. Handling and treating the waste, while providing as much protection as possible to the workers and the community, increases the costs associated with the trains and makes them more difficult to implement.

Finally, the model provides deterministic sensitivity analysis on the CERCLA criteria weights and the evaluation measure scores associated with the top-ranked train. Sensitivity analysis on the weights shows the top ranked train's insensitivity towards changes in the individual weights. Sensitivity analysis on train 15's measure scores shows that the amount of principal threats treated and irreversibility scores will cause a change in rankings if updated data determines that the percent of principal threats treated or percent of waste in an irreversible form fall below 56 (while scores for every other measure stay the same).

5. Findings and Conclusions

5.1 Conclusions

This research provides a deterministic decision analysis model (implemented in Logical Decisions and DPL) to aid the decisionmakers at INEEL in choosing a remediation strategy for the SDA that best meets the criteria defined by CERCLA. Value-focused thinking techniques and the CERCLA document helped create the decisionmakers' fundamental objectives hierarchy. The decisionmakers' hierarchy consists of five top-level fundamental objectives (CERCLA's balancing criteria) that are decomposed and quantified into a set of 21 measures. Finally, multiattribute preference theory techniques were used to determine weights associated with each fundamental criterion and convert evaluation measure scores into value based on decisionmakers' preferences.

The decision analysis model uses the decisionmakers' weights and value functions to convert a train's performance in the 21 measures into component values for each of the five CERCLA balancing criteria. Finally, an additive value function combines the component values of the five balancing CERCLA criteria to determine each train's ability to meet the decisionmakers' strategic objective, maximum CERCLA compliance.

The decision analysis model provides helpful visual aids that present each train's overall value and the value of each CERCLA balancing criterion. In addition the model can perform sensitivity analysis on not only the weights associated with each CERCLA criterion, but also the evaluation measure scores associated with the top-ranked train.

The weight sensitivity analysis shows the insensitivity of the top-ranked train to changes in the criteria weights. The score sensitivity analysis shows which measures, when varied from their nominal values, are most influential in changing the top ranked train; indicating which measures may need more detailed modeling that accounts for the uncertainty.

The values of each CERCLA balancing criterion were used to create scatter plots versus the net present value. These scatter plots not only showed which trains were not dominated in each criterion, but they also showed the tradeoffs between certain categories of trains against the CERCLA criteria.

Finally, the act of developing the model as a participative, cooperating effort between decisionmakers at INEEL, EPA, and Idaho has helped focus discussion and decisionmaking of this problem. Insight gained from these efforts, as well as this document, can be used as part of a well documented Record of Decision.

5.2 Recommendations

The results from the decision analysis model suggest that if the decisionmakers feel the long-term benefits of treating the wastes are worth the increased cost and short-term risks to workers and community, they should choose one of the in-situ vitrification technologies. The four in-situ vitrification technologies score very well in overall value while costing about the same as the *non*-ex-situ treatment trains. In fact, two of the in-situ vitrification trains are on the overall value efficiency frontier (trains 15 and 23); indicating these trains are not dominated by any other train.

If the decisionmakers decide to use an in-situ vitrification train, this analysis (based on best available data) indicates they should choose between train 15 and 23. Train 23's overall value (without factoring the cost value) is 0.319 less than train 15's. However, train 15 costs over $88 million more than train 23. INEEL remediation decisionmakers and other stakeholders must determine if train 15's increased value warrants the additional cost.

If the INEEL decisionmakers decide that treating the waste directly is *not* worth the increased costs and short-term risks to the community, they should consider train 12. Train 12 is the least expensive, easiest to implement, and provides the greatest short-term effectiveness of all the non-Basic trains (trains 4 - 28). These factors, coupled with the fact that train 12 does provide some value in the reduction of toxicity, mobility, or volume criterion (through soil vapor extraction) make train 12 the highest ranked train after the four in-situ vitrification trains.

In addition to providing insight into which trains score well against the CERCLA balancing criteria, this research identifies which trains do *not* score well against the CERCLA balancing criteria based on the current data. Information on inefficient technologies can help the decisionmakers at INEEL decide which technologies to stop considering for further evaluation or indicate which areas they must improve to warrant further evaluation.

The scatter plots of cost versus overall value (without the cost contribution) show that the engineered vaults, three of the four in-situ grouting trains, and the ex-situ trains are dominated by technologies along the efficiency frontier. The engineered vaults are

dominated in overall value because they are relatively expensive, provide little short-term effectiveness, and do nothing to treat the waste.

Performing soil vapor extraction before excavating the waste may help improve the overall value of these trains. However, it would be unlikely to improve the train rankings enough to warrant further consideration. Soil vapor extraction would provide value on the reduction of toxicity, mobility, or volume balancing criterion. However, the value would likely be similar to the value provided by the multiple containment systems (since soil vapor extraction is the only treatment performed in both categories). Since the vaults cost about three times more than the multiple containment systems, they are still dominated by the multiple containment systems on every balancing criterion. Thus, the improvement in overall value would be insufficient to warrant further consideration of the engineered vaults studied in this analysis.

The only grouting train that appears to warrant further consideration is train 14, traditional in-situ grouting. The other grouting trains first excavate the waste, sort and place the waste into another pit, then grout the waste. While this increases the grout's long-term effectiveness and performance towards the reduction of toxicity, mobility, or volume criterion, the excavation process increases the costs and decreases the implementability and short-term effectiveness of the grouting trains. As a result, the multiple containment systems, which cost about the same but produce more overall performance, dominate these grouting trains.

Finally, the decisionmakers must determine if the expense of the ex-situ treatments are worth their price. The in-situ vitrification trains perform as well as the ex-

situ treatments, but they are safer to workers and the community, and cost much less. However, this analysis did not take into consideration any benefits associated with the fact that train 26 is currently under pilot testing. Capital costs already expended have been treated as sunk costs. In addition, much of the uncertainty (to be discussed in the section 5.4) associated with the scores for train 26 may be less than the uncertainty associated with in-situ vitrification, a relatively innovative technology for sites like the SDA.

Even though these recommendations are made under the assumption of certainty of the data and site parameters, these assumptions do not accurately reflect the true state of the SDA. Chapter 4 showed that changes in the cost values could change the trains on the efficiency frontier and that changes in some of measure scores can switch the rankings of the top two trains. The next section addresses how these concerns and simplifying assumptions, used in the decision analysis model in this study, can be addressed in succeeding efforts to improve the worth of the decision analysis models to the decisionmakers at INEEL.

5.3 Major Contributions

A major contribution of this research is the development of a set of evaluation measures that *quantify* a remediation train's ability to meet each of the decisionmakers' fundamental objectives in the CERCLA-based SDA hierarchy. Quantifiable measures are useful because individuals or groups questioning the results can review the quantitative measures and the scores of the disputed trains and identify how the scores were

developed. If the individuals or groups question the decisionmakers scores, they can enter their own scores to see if there is a change in the decision.

Perhaps even more valuable than the set of quantifiable measures is the set of component value functions that convert the remediation train scores into dimensionless component values quantifying a train's value to the decisionmakers based on their preferences and attitudes towards marginal rates of return for train performance. In addition, this research provides an additive value function that clearly shows how the component values are combined to produce an overall value quantifying how well a train meets the CERCLA criteria. Once again, this is useful because individuals or groups disagreeing with the decisionmakers' results can examine the decisionmakers' component value functions and the parameters of additive value function. Individuals or groups disagreeing with any of the component value function forms or parameters of the additive value function can enter their preferences into the model to see if there is a change in the decision.

In conclusion, this research provides a transparent, defensible, interactive decision analysis model that ranks remediation trains based on the decisionmakers' values. The model parameters and value functions are easily modified to address questions and/or concerns from individuals or groups disputing the decisionmakers' decision. Furthermore, the model can be easily changed and updated to fit the needs and demands of environmental remediation decisionmakers at other DOE sites in other EPA regions.

5.4 Recommendations for Future Research

This research was intended to be the "first cut" towards creating a CERCLA-based decision analysis model that accurately depicts the alternatives associated with the SDA and the decisionmakers' preferences. Throughout this research, simplifying assumptions were made that should be addressed in future studies. These assumptions, as well as other suggestions, are provided in the following sub sections.

5.4.1 Threshold Criteria Modeling

This research assumes that each train meets the two threshold criteria: overall protection of human health and the environment and compliance with ARARs. This is a reasonable assumption for this research as the study incorporates the best available, although admittedly limited data, on the SDA site and the remediation trains. However, the INEEL continues to gather more data on the site and on all of the technology trains. In the future, engineers at INEEL may determine that some of the trains no longer apply to the site or have a high probability of not meeting the threshold criteria. Such an event is not unlikely. During this analysis train 13 was removed from consideration because engineers determined that in-situ vitrification, without a form of pretreatment, could not be performed on the site. This was a significant change because train 13 was the top ranked train before it was removed. Thus, a future effort may want to model the threshold criteria as well as the five balancing criteria.

5.4.2 Uncertainty Modeling

This research assumes the parameters of the SDA are known and that the evaluation measure scores associated with each train for each measure are known. This is

not the case. There is uncertainty associated with the volume of waste in the pits and trenches as well as the contents within them. These uncertainties will influence the costs associated with each train, as well as many of the developed evaluation measures. Some trains perform well when remediating organics but poorly when remediating non organics (or vice versa). As the ratio between organics and non organics changes, so do the performance parameters of many of the treatment technologies. While this report's sensitivity analysis attempted to consider the effects of some uncertainty, modeling the cost and performance uncertainties would greatly improve the value of the models to the decisionmakers; giving them better insight into the inherent risks associated with each train.

Finally, further research may wish to consider the costs and benefits of performing a pilot study for the in-situ vitrification technologies. Obviously a pilot study will cost more money. However the study should reduce the uncertainty associated with in-situ vitrification costs and performance values. A value of information study can help determine whether or not the reduced uncertainty would be worth the cost of the pilot study for the in-situ vitrification technologies.

5.4.3 Determine Mutually Preferential Independence

This analysis assumes the CERCLA criteria are mutually preferential independent to the decisionmakers. This is a reasonable assumption for this research because the decisionmakers tried very hard to develop performance measures independent of other CERCLA criterion measures. In addition, the goal of this research was to approximate a train's value towards CERCLA compliance. The literature suggests that mutually

preferential independence is a fair approximation to make in such circumstances. However, future research should verify that this is indeed true.

5.4.4 Performance Against Principal Threats

At the time of this analysis, the engineers at INEEL had not determined the site's principal threats. This problem was handled by assuming that the principal threats were separated into the three categories mentioned in Chapter 3: VOC's, TRU, and LLW. Each of these categories contained 3 to 7 specific elements and compounds. Trains that treated these wastes received increased component value scores through the reduction of toxicity, mobility, or volume through treatment criterion. Since treating these wastes is of such importance, any future work must verify that the substances believed to be the principal threats have not changed; or if they do change, modify the model appropriately.

5.4.5 Modeling Decisionmakers' Objectives

Three of the 21 evaluation measures have little to no impact on the overall value because all 27 trains score almost the same for these evaluation measures. These measures are: plant impacts, animal impacts, and degree of management required. This was due, in part, because trains that where not believed to meet these standards were not considered for this site by INEEL personnel. Measures having no impact on the decision reduce the differences between the trains (because each criterion has the same score). Future studies may need to find evaluation measures that account the any meaningful difference between the trains.

Future research may need to modify how the reduction of toxicity, mobility, or volume through treatment criterion is modeled. This research breaks this criterion into so

many sub criteria, categories, and sub categories that the weights associated with some of the measures are less than one percent of the total weight. This may not accurately reflect every decisionmakers' values. For example, train 25 performs relatively well in the reduction of toxicity, mobility, or volume through treatment criterion. However the process creates enormous amounts of treatment residuals, making the train undesirable. Unfortunately, the effective overall weight associated with the volume of treatment criterion is 1/72; hardly enough to have major impact on the overall value. Future research may want to simplify this criterion so that only the most important aspects of the criterion are taken into account.

5.4.6 Parallel Versus Series Remediation of Pits and Trenches

The analysis in this study assumed that each remediation train remediated the pits and trenches one at a time (in series). Some remediation trains may be effective in remediating more than one pit or trench at a time (in parallel). While remediating in parallel may require greater capital costs, it might reduce the operations and management costs for some trains. In addition, remediating in parallel would likely reduce the time to remediate the site. For these reasons, a future study may wish to explore whether or not operating in parallel provides greater value for the decisionmakers.

5.5 Summary

Selecting the remediation train that best meets the CERCLA criteria is a very complex problem involving considerable effort and cost by a variety of stakeholders. The decisionmakers' reasons for selecting a particular remediation strategy must be sound and

transparent so the decision can be presented to the public and accepted as a logical, supportable (or defensible) choice.

Value-focused thinking and multiattribute preference theory, when applied to decision analysis techniques, provide a structured method for analyzing this complex problem. Value-focused thinking ensures that alternatives are ranked according to the decisionmakers' values, rather than against other alternatives. Multiattribute preference theory quantifies the decisionmakers' values and preferences, as well as an alternative's ability to meet those values. Finally decision analysis modeling techniques combine these two processes to produce useful information to the decisionmakers that show how well alternatives meet their objectives, as well as, how sensitive (or insensitive) these rankings are to changes in the model parameters.

While these techniques cannot produce a model that accounts for all of the interactions and details involved in the remediation selection process, they can provide valuable insight towards those values and parameters that have the largest influence on the final result. This ultimately allows the decisionmakers to make better informed and defensible decisions.

Appendix A: Pit and Trench Areas and Volumes

Table A.1 Pit areas and volumes (TRM-04-95).

Location	**Area ft^2**	**Volume ft^3**
P 1	24,913	353,765
P 2	78,425	1,113,635
P 3	41,830	593,986
P 4	111,732	1,581,284
P 5	108,754	1,544,307
P 6	54,984	780,773
P 7	300	1,200
P 8	31,294	444,375
P 9	45,541	646,682
P 10	111,732	1,586,594
P 11	24,859	352,998
P 12	29,910	424,722
P 13	19,290	273,918
P 14	40,704	577,997
P 15	74,805	1,062,231
P 16	22,246	315,893
P 17	66,587	945,535
P 18	49,652	705,058
Acid Pit	21,291	302,332

Table A.2 Trench areas and volumes (TRM-04-95).

Location	Area ft^2	Volume ft^3
T 1	8,043	114,211
T 2	8,015	113,813
T 3	7,777	110,433
T 4	7,812	110,930
T 5	8,155	115,801
T 6	7,826	111,129
T 7	8,120	115,304
T 8	7,826	111,129
T 9	8,610	122,262
T 10	8,092	114,906
T 11	6,279	89,162
T 12	12,502	177,528
T 13	5,439	77,234
T 14	10,969	155,760
T 15	5,495	78,029
T 16	10,801	153,374
T 17	4,270	60,624
T 18	7,175	101,885
T 19	9,905	140,651
T 20	7,000	99,400
T 21	2,625	37,275
T 22	2,653	37,673
T 23	3,093	43,935
T 24	2,947	41,847
T 25	7,000	99,400
T 26	3,115	44,233
T 27	7,007	99,499
T 28	3,094	43,935
T 29	2,422	34,392
T 30	7,014	99,599
T 31	3,101	44,034
T 32	2,457	34,889
T 33	7,007	99,499
T 34	2,280	103,376
T 35	7,007	99,499
T 36	8,603	122,163
T 37	7,000	99,400
T 38	6,419	91,150
T 39	6,993	99,301
T 40	7,287	103,475
T 41	7,000	99,400
T 42	7,952	112,918
T 43	6,664	94,629
T 44	3,500	49,700
T 45	7,959	113,018
T 46	6,699	95,126
T 47	7,966	113,117
T 48	6,685	94,927
T 49	7,728	109,738
T 50	6,601	93,734
T 51	7,987	113,415
T 52	6,349	90,156
T 53	8,050	114,310
T 54	6,370	90,454
T 55	8,134	115,503
T 56	8,134	115,503
T 57	6,342	90,056
T 58	6,447	91,547

Appendix B: SDA Value Hierarchy and Measures

The purpose of this appendix is to quantify CERCLA's (Comprehensive Environmental Response Compensation Liability Act) five balancing criteria. All information about CERCLA requirements are derived from "Guidance for Conducting Remedial Investigations and Feasibility Studies Under CERCLA, Interim Final" EPA/540/G-89/004. The CERCLA criteria and the associated components for each criterion are illustrated in the figure below.

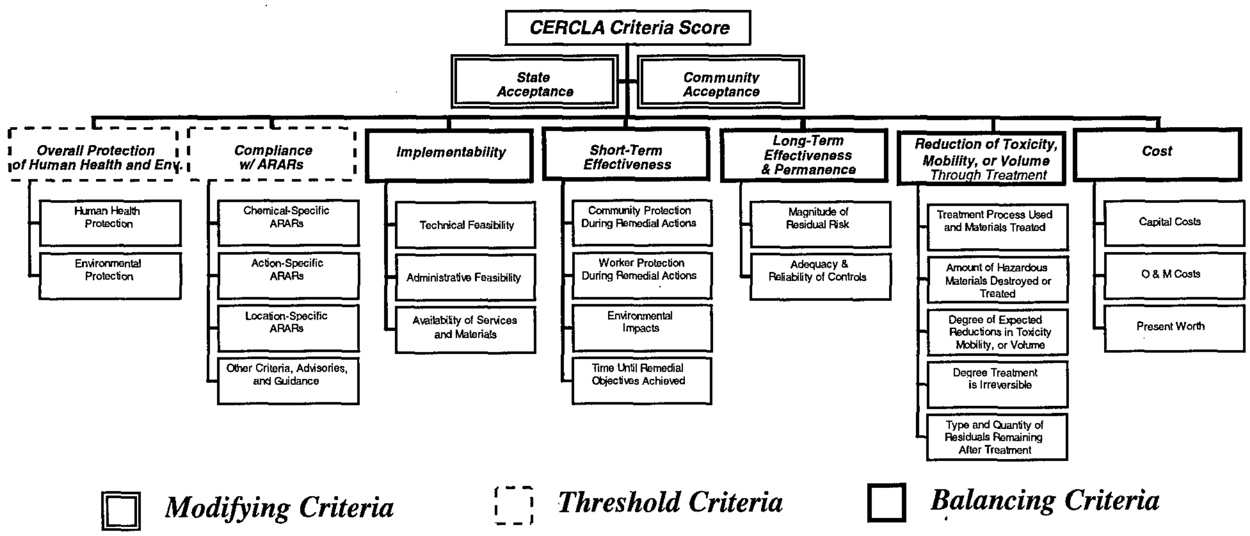


Figure B.1 CERCLA guidance objectives hierarchy.

State and community acceptance are not included in this analysis since they are modifying criteria addressed after releasing the ROD (Record of Decision) to the public. Overall protection of human health and the environment and compliance with ARARs (Applicable or Relevant and Appropriate Requirements) are threshold objectives that all evaluated alternatives must meet.

Discussions with decisionmakers from INEEL, EPA, and Idaho resulted in a fundamental objectives hierarchy (based on CERCLA guidance) for the SDA. This hierarchy is presented in figure B.2

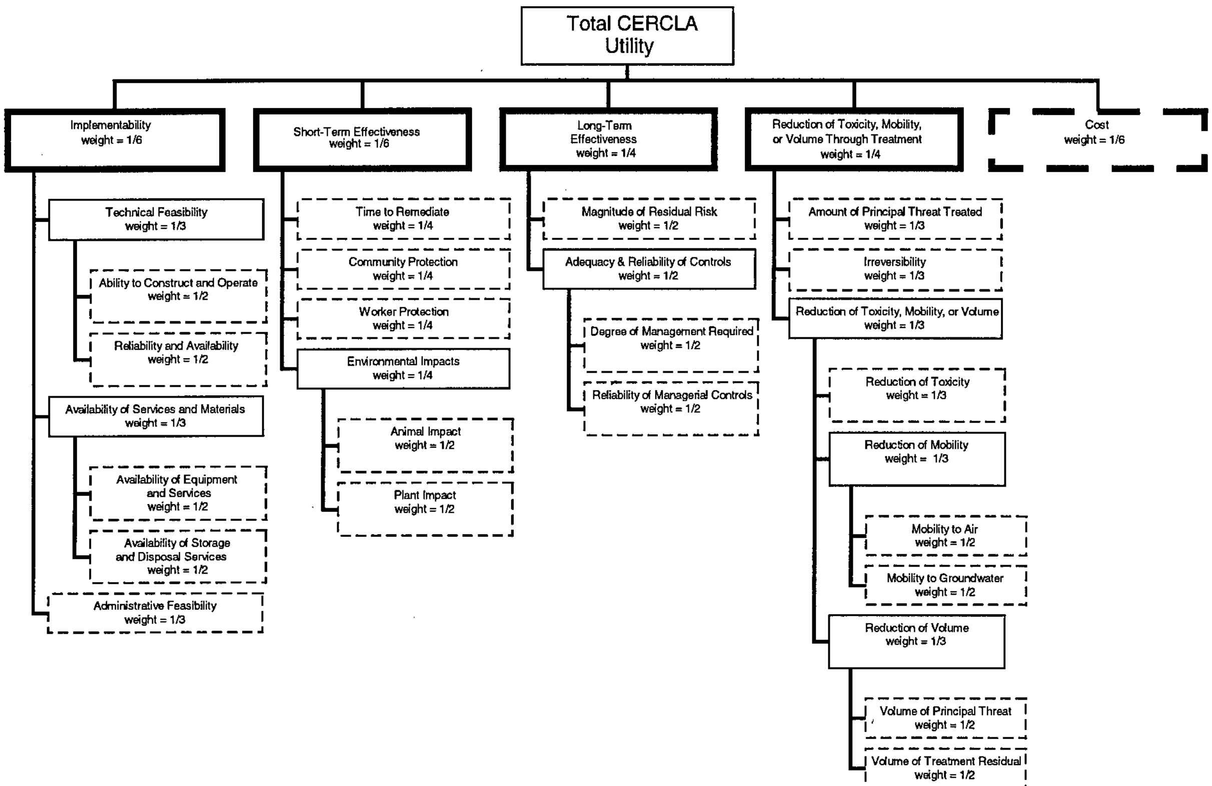


Figure B.2 CERCLA based fundamental objectives hierarchy for the SDA.

The remainder of the appendix addresses the logic behind the structure of the fundamental objectives hierarchy. In addition, this appendix explains how each CERCLA balancing criterion is quantified. This is achieved by breaking each criterion into sub criteria. Sub criteria can be further broken into categories. The sub criteria or categories (if used) are quantified by evaluation measures with associated component value functions. Criteria with evaluation measures are outlined in figure B.2 with dashed boxes. The component value for the worst possible outcome of each measure is zero

while the component value for the best possible outcome for each measure is ten. The component value functions determine intermediate scores.

Almost all of the component value functions for the measures are linear with either an increasing or decreasing slope. The fact that the function is linear implies that the change in value associated with a change in the x-axis score at any position in the x-axis is the same as a change in value associated with a similar change in the x-axis score anywhere else on the x-axis. A positive slope implies the greater the x-axis score, the better an alternative meets the criterion. A negative slope implies the less the x-axis score, the better an alternative meets the criterion. Explanations of component value function shapes are given whenever the function is *not* linear.

Implementability.

"The implementability criterion addresses the technical and administrative feasibility of implementing an alternative and the availability of various services and materials required during its implementation. This criterion involves analysis of the following factors: technical feasibility, administrative feasibility, and availability of services and materials (EPA/540/G-89/004, 6-9)."

Other factors suggested for inclusion in this objective are ease of additional remedial actions and ability to monitor effectiveness. These factors are not measured explicitly in this analysis because they are addressed in operations and maintenance costs and the long-term effectiveness measures.

Technical Feasibility - This sub criterion of implementability addresses the ability to construct and operate the remediation alternative and the reliability and availability of the technology. This sub criterion is broken into two categories to address both of issues.

- Ability to construct and operate the alternative.

This sub-criterion category satisfies CERCLA's requirement of addressing the technical difficulties and unknowns associated with a technology (EPA/540/G-89/004, 6-9).

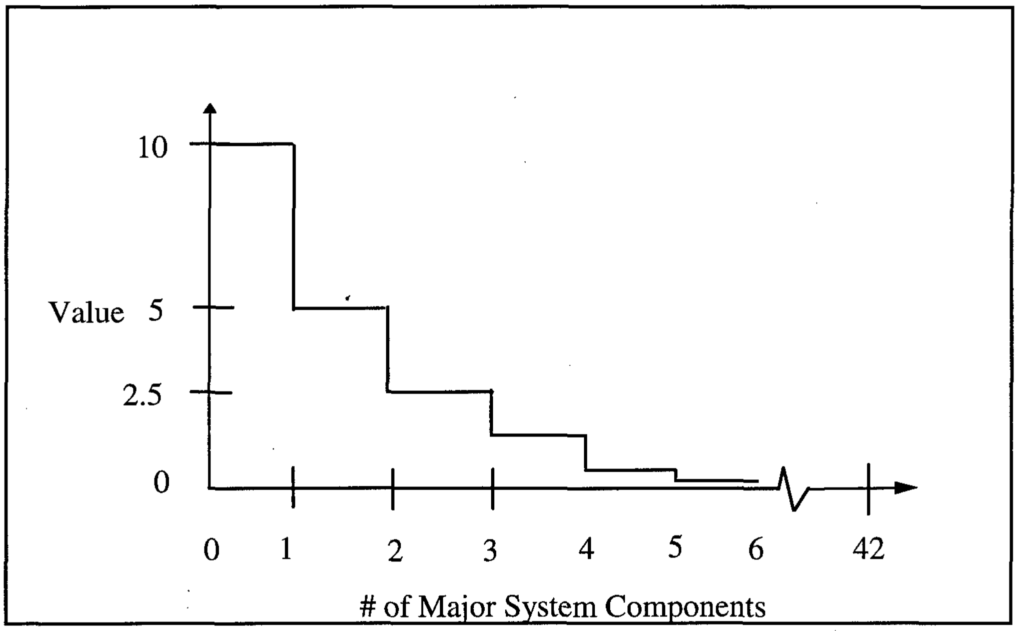


Figure B.3 Ability to construct and operate measure component function.

The greater the major system components, the more difficult the alternative is to construct and operate. A system with one system receives a value of 10. For every system added after one, the value is reduced by half. For example, two major system components yields a score of 5 and three major system components yields a score of 2.5, etc. Thus the function is,

$$Value = 10 \times \left(\frac{1}{2}\right)^{i-1} \quad \text{for i = 1 to 42,}$$

where i is the number of system components. Forty two is the maximum number of major system components among all of the alternatives.

- Reliability of the Alternative.

This sub-criterion category satisfies CERCLA's requirement of addressing the likelihood that technical problems associated with implementation will lead to schedule delays.

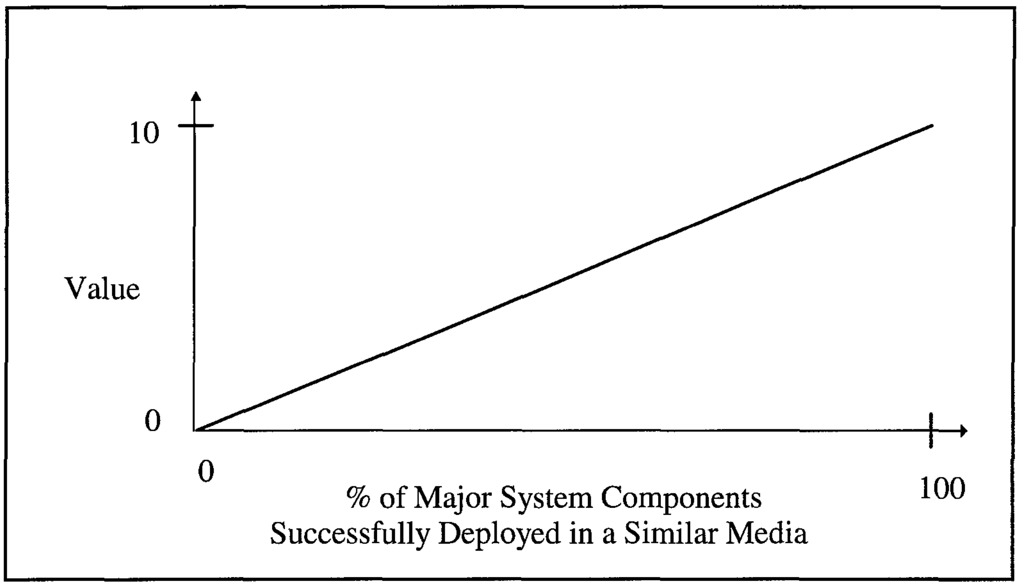


Figure B.4 Reliability measure component value function.

The more system components successfully deployed in similar medium, the more reliable the alternative.

- *Availability of services and materials.*

This sub criterion addresses the availability of treatment storage capacity and disposal services, availability of necessary equipment and specialists, and the availability of prospective technologies (EPA/540/G-89/004, 6-9). This sub criterion is broken into two categories addressing the issues just mentioned.

- Availability of Necessary Equipment and Specialists and Prospective Technologies.

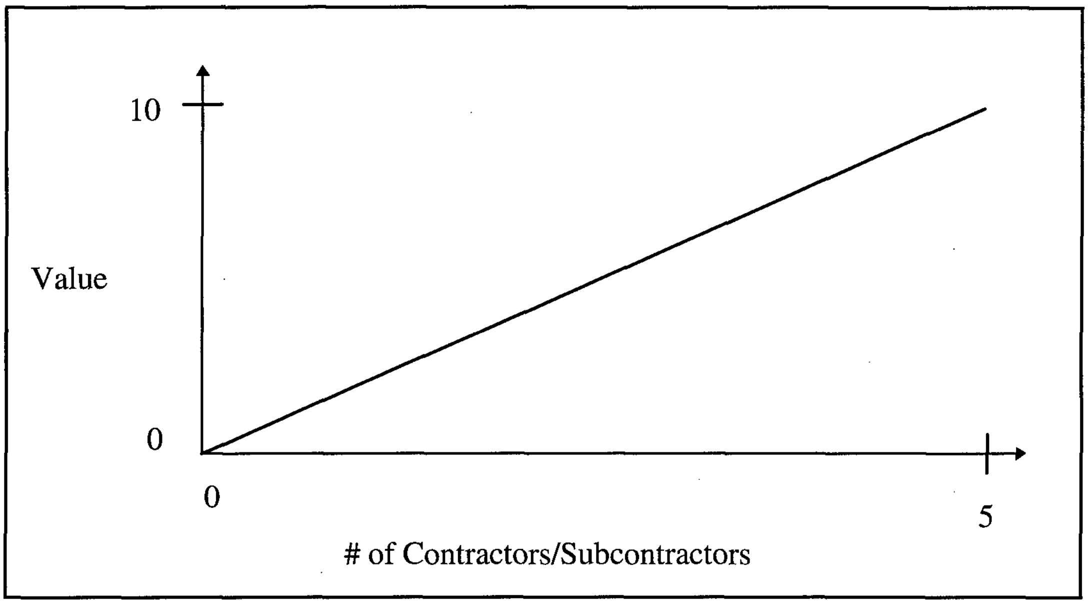


Figure B.5 Availability of necessary equipment and specialists and prospective technologies measure component value function.

The x-axis is either the number of contractors available or the number of subcontractors available, depending on the limiting factor. In some cases there may be several subcontractors for all or most of the technologies, but only a few subcontractors are willing to place a bid for the entire remediation process. In this situation the number of contractors is the limiting factor. In other situations there may be several contractors that can place bids, but all must subcontract a particular procedure to the same company (GEOSAFE for in-situ vitrification for example). In this situation the number of subcontractors is the limiting factor.

Regardless of which is the limiting factor, the more contractors/subcontractors available the greater the availability of services and materials and competitive bids. Alternatives that have no available contractors/subcontractors have zero value.

Alternatives that have at least five contractors/subcontractors have a value of 10. There is no increase in value if there are more than five contractors/subcontractors.

- Availability of Storage and Disposal Services.

This sub criterion satisfies CERCLA's requirement of addressing the availability of treatment, storage capacity, and disposal services (EPA/540/G-89/004, 6-10).

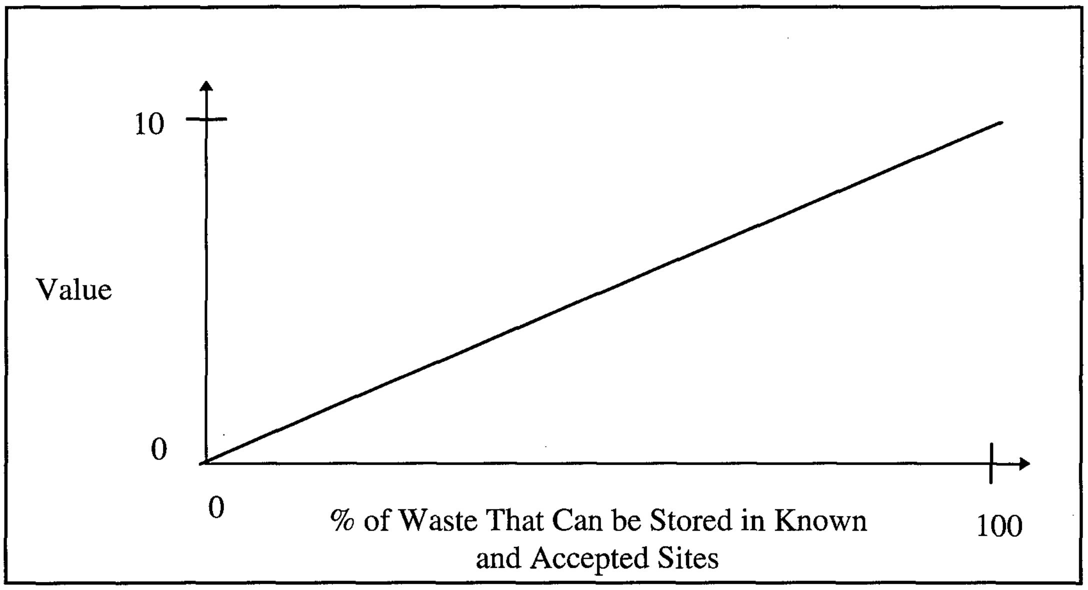


Figure B.6 Availability of storage and disposal services measure component value function.

This measure quantifies the availability of disposal sites relative the wastes in the pit. The greater the percentage of waste that can be stored in known and accepted sites, the better.

- Administrative Feasibility

This sub criterion satisfies CERCLA's requirement for addressing the ability to obtain approval and coordinate with other offices and agencies.

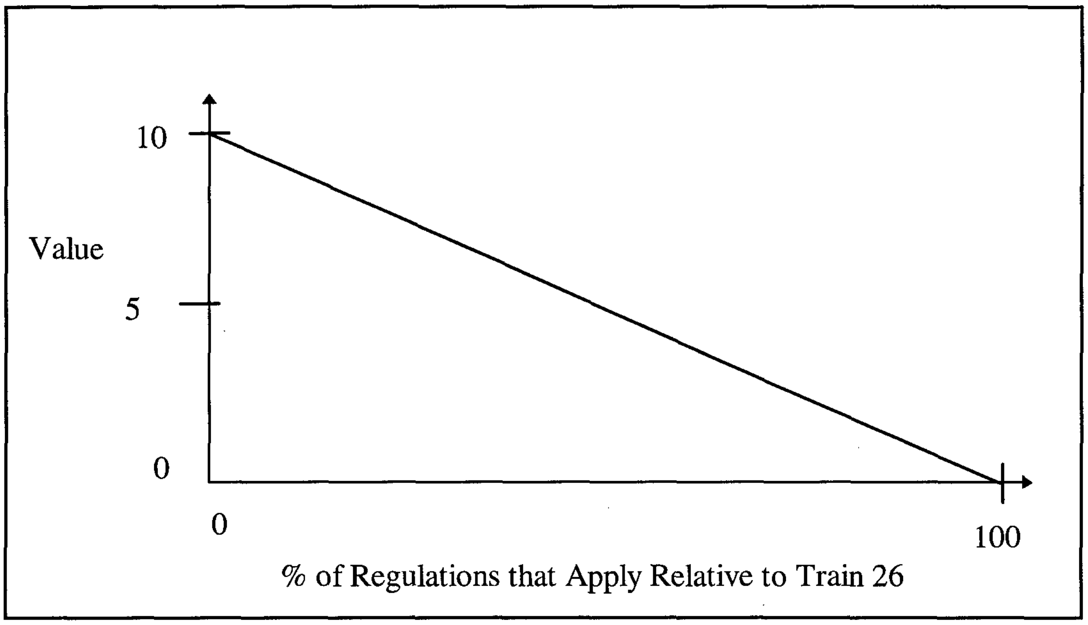


Figure B.7 Administrative feasibility measure component value function.

The more regulations that apply to the alternative, the more administrative work and coordination is required. Eventually this measure will change to actual number of regulations. For this analysis the Train 25 process (gantry building, chemical pretreatment, plasma furnace and disposal to WIPP) was assumed to have the most regulations and all other alternatives were scored relative to this alternative.

Short-Term Effectiveness

"This evaluation criterion addresses the effects of the alternative during the construction and implementation phase until remedial response objectives are met. Under this criterion, alternatives should be evaluated with respect to their effects on human health and the environment during implementation of the remedial action. The following should be addressed as appropriate for each alternative: protection of the community during remedial actions, protection of workers during remedial actions, environmental impacts, and time until remedial response objectives are achieved (EPA/540/G-89/004, 6-9)."

- Time Until Remedial Response Objectives are Achieved.

This sub criterion satisfies CERCLA's requirement of estimating the time required to achieve protection for the entire site (EPA/540/G-89/004, 6 - 9).

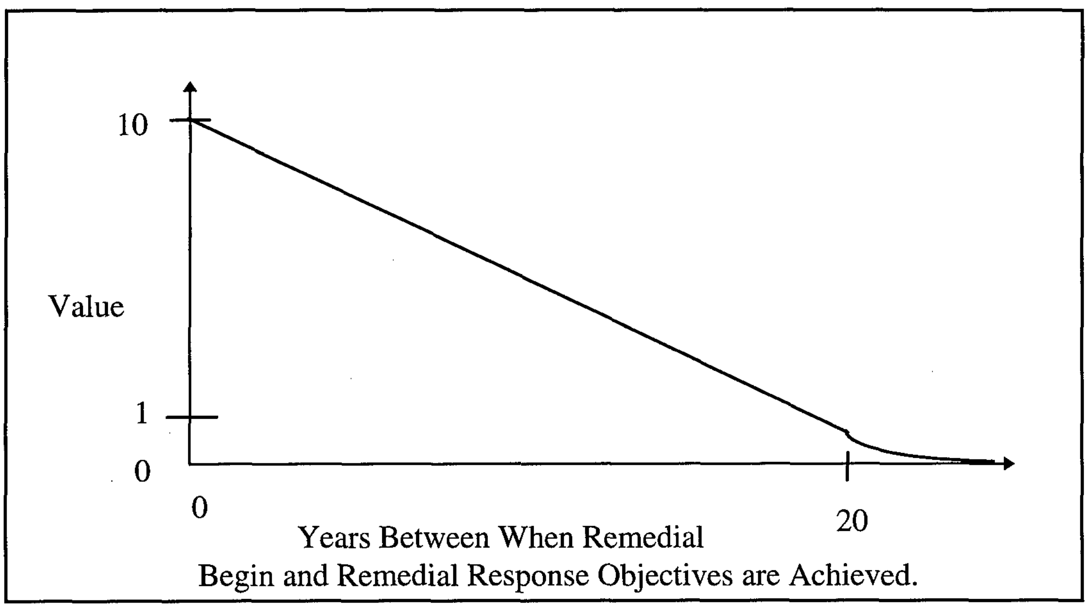


Figure B.8 Time until remedial response objectives are achieved measure component value function.

There is no statutory mandate on a completion time for subsurface waste. However, shorter remediation time is better than longer. There is very little value once the time reaches twenty years. The exponential drop in value after twenty years indicates that even though there is little value after twenty years, there is never a point (except infinity) where there is zero value. An alternative only has value if it achieves the remedial objectives.

- **Community Protection.**

This sub criterion satisfies CERCLA's requirement of addressing protection of the surrounding community during the remedial action. "This aspect ... addresses any risk that results from implementation of the proposed remedial action, such as dust from excavation, transportation of hazardous materials, or air-quality impacts from a stripping tower operation that may affect human health (EPA/540/G-89/004, 6 - 9)."

The sub criterion is based on the idea that risk to the community depends upon the probability of an occurrence and the consequence of that occurrence. To quantify this sub criterion the following heuristic was created.

safety of community value = 10 - (prob. of an event) × (consequence of the event).

Thus, an alternative that either has no probability of an event (during implementation) or has no consequence associated with an event (or both) receives a perfect value of ten. Alternatives that have probabilities and consequences of bad events must receive a value less than ten. The value is found using the following relationships.

probability of an event = 0.1 times the # of years until remedial objectives are met.
= 1.0 when the # of years until remedial objectives are met is greater than ten.

consequence of the event = 0 when nothing is done to the site.

= 2 when the waste is contained.

= 4 when the waste is treated in situ.

= 6 when the waste is excavated.

= 8 when the waste is treated ex situ.

= 10 when waste is shipped off site.

This measure is not designed to be an exact calculation of the risks associated with an alternative during the implementation phase. The heuristic works under the idea that the longer an alternative is in operation, the greater the threats posed to community. Containment provides less risk to the community than in-situ treatment, which provides less risk than excavation and ex-situ treatment. Finally, transportation off-site presents the greatest potential risk to the surrounding community because of increased possibility of direct exposure to waste through an accident or sabotage.

Note: If a technology has two of the above consequences, then the greater consequence is applied to the calculation. For example if an alternative excavates the waste (consequence = 6) as a pretreatment for in-situ vitrification (consequence = 4), then the consequence value is 6.

- Worker Protection.

This sub criterion satisfies CERCLA's requirement of addressing protection of workers during the remedial action. "This factor assesses threats that may be posed to workers and the effectiveness and reliability of protective measures that would be taken (EPA/540/G-89/004, 6 - 9)."

The sub criterion is based on the idea that risk to the workers depends upon the probability of an occurrence and the consequence of some occurrence. To quantify this sub criterion the following heuristic was created.

worker safety value = 10 - (probability of an event) × (consequence of the event).

Thus, an alternative that either has no probability of an event or has no consequence associated with an event (or both) receives a perfect value of ten. Alternatives that have probabilities and consequences of bad events must receive a value less than ten. The value is found using the following values.

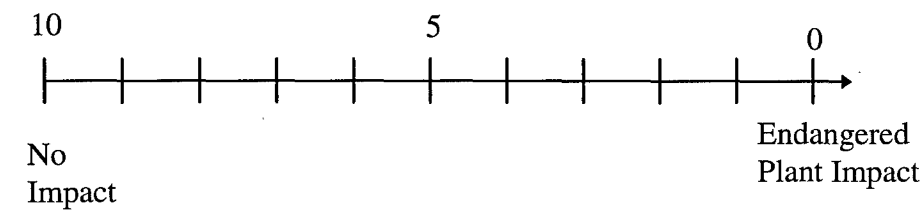
probability of an event	= 0.1 times the # of major system components.
	= 1.0 when the # of major system components is greater than ten.
consequence of the event	= 0 when nothing is done to the site.
	= 2 when the institutional controls are implemented.
	= 4 when the waste is contained.
	= 6 when the waste is stabilized or treated in situ.
	= 8 when the waste is retrieved.
	= 10 when waste is treated ex situ.

This measure is not designed to be an exact calculation of the risks associated with an alternative. The heuristic works under the idea that the more major components in an alternative the greater the threats posed to workers. In addition, the more the waste is handled the greater the threats posed to workers. Finally, handling the waste ex-situ posses more threats to workers than handling waste in-situ.

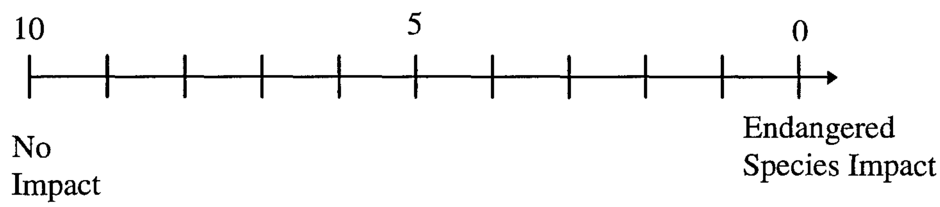
- Environmental Impacts.

This sub criterion satisfies CERCLA's requirement of addressing the potential for adverse environmental impacts that may result from the construction and implementation of an alternative. The measure is broken into two categories, plants and animals. Each category is a qualitative measure that captures the impact an alternative has on plants and animals. The worst possible outcome is having an alternative that has an impact on endangered plant or animal species. The best possible outcome is an alternative that has no impact on plant and animals.

- Plant Impact.



- Animal Impact.



Long-Term Effectiveness.

"The evaluation of alternatives under this criterion addresses the results of a remedial action in terms of the risk remaining at the site after response objectives have been met. The primary focus of the evaluation is the extent and effectiveness of the controls that may be required to manage the risk posed by treatment residuals and/or untreated wastes. The following components of the criterion should be addressed for each alternative: magnitude of residual risk and adequacy and reliability of controls" (EPA/540/G-89/004, 6-8).

- **Magnitude of Residual Risk.**

"This factor assesses the residual risk remaining from untreated waste or treatment residual at the conclusion of remedial activities. The potential for this risk may be measured by numerical standards such as cancer risk levels or the volume or concentration of contaminants in waste, media, or treatment residuals remaining on the site. The characteristics of the residuals should be considered to the degree that they remain hazardous, taking into account their volume, toxicity, mobility, and propensity to bioaccumulate (EPA/540/G-89/004, 6-8)."

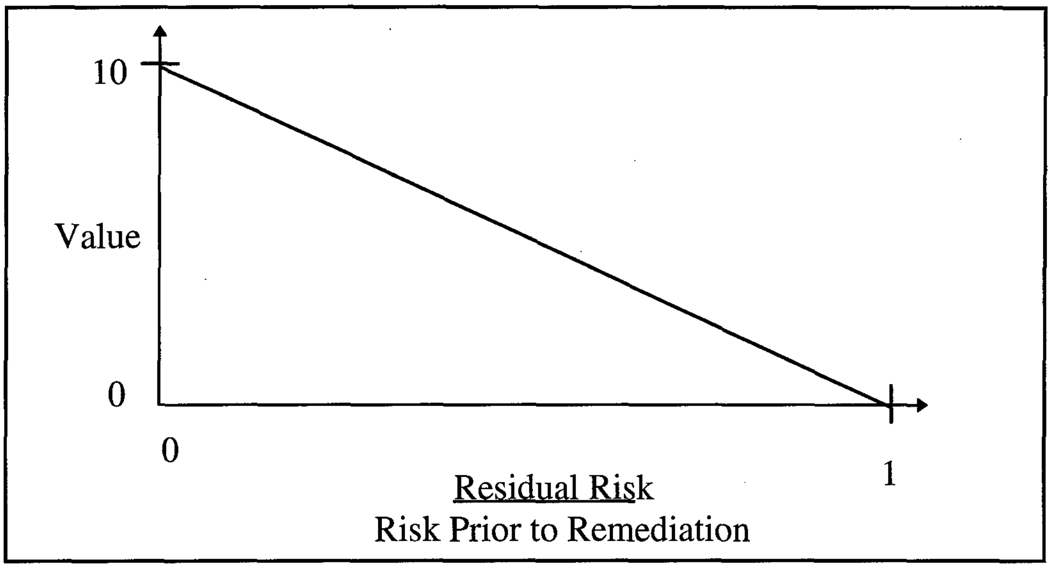


Figure B.9 Magnitude of residual risk measure component value function.

This measure is quantified by dividing the risk measure after remediation by the risk measure prior to remediation. Obviously the closer the fraction is to one, the lower the value. Risks associated with the alternatives and the site will be provided in the baseline risk assessment (BRA).

- Adequacy and Reliability of Controls.

This sub criterion satisfies CERCLA's requirement of addressing the adequacy and suitability of controls used to manage treatment residuals or untreated wastes that remain at the site. To provide greater sensitivity, the sub criterion is broken into two categories: degree of management required and reliability of managerial controls.

- Degree of Management Required.

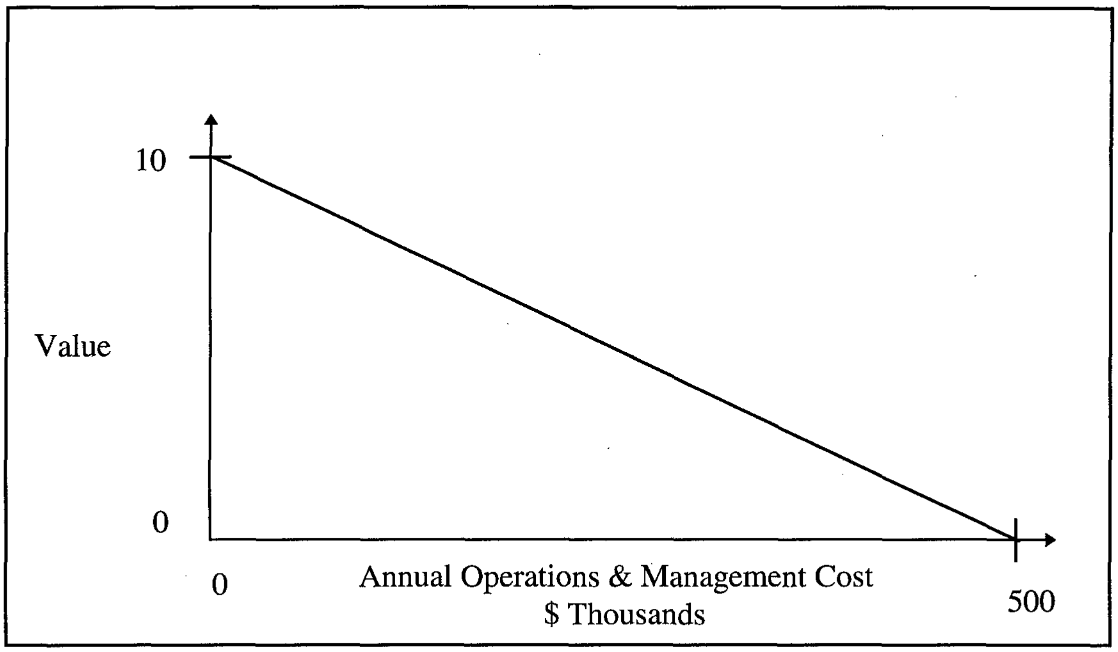


Figure B.10 Degree of management required measure component value function.

This sub - criterion category addresses the concerns of CERCLA (EPA/540/G-89/004, 6-9):

1. Type and degree of long-term management required -- the more complex the management, the more expensive it will be.
2. Requirements for long-term monitoring -- the more requirements needed, the greater the cost.
3. Operation and maintenance functions that must be performed -- the more complex and involved the operations and management, the more expensive the alternative.

In addition, this measure addresses the concern of site management should the DOE no longer exist or provide support in the future.

Although a similar measure is part of a net present value calculation (used under the cost criterion), this measure is not the same. This measures the operations and management costs *after* the alternative is implemented and the dollars are not discounted over time. Discounting the dollars over the long-term tends to reduce the differences

between alternatives with costly managerial controls and inexpensive managerial controls. By not discounting the dollars over time, the difference between the two extremes remains the same.

- Reliability of Managerial Controls,

This sub - criterion category satisfies CERCLA's requirement of addressing: the potential need for replacement of technical components, magnitude of threats or risks should the remedial action need replacement, and degree of confidence that controls adequately handle potential problems (EPA/540/G-89/004, 6 - 8).

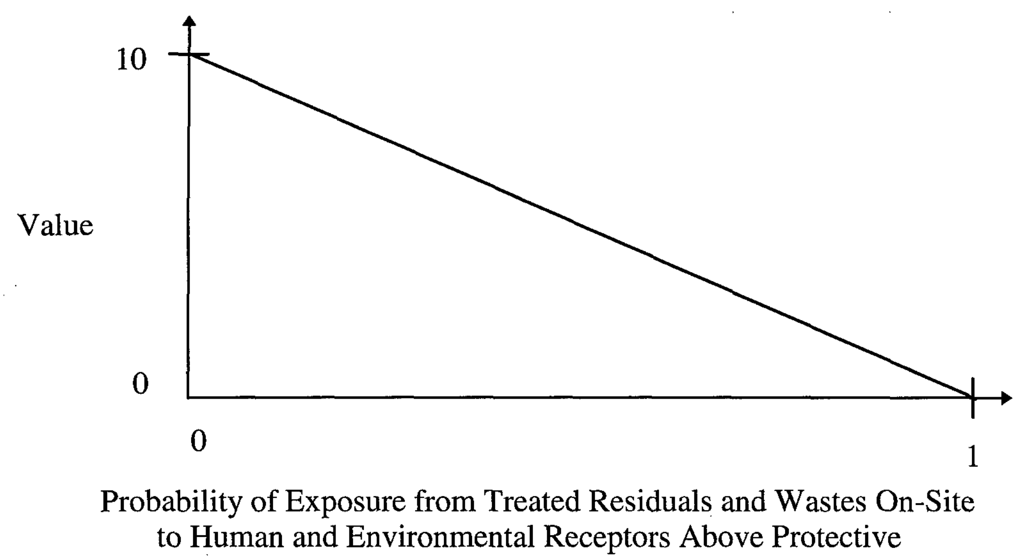


Figure B.11 Reliability of managerial controls measure component value function.

The measure is self explanatory and taken directly from the CERCLA document, however the relative magnitude of the risk is not accounted for in this measure. This analysis assumes that exposure to human and environmental receptors above protective levels is unacceptable regardless of the contaminant. Another way of viewing this

assumption is if there is a probability that contaminant A (which is relatively harmless) will be exposed to the humans or the environment, then the same probability is associated with contaminant B (which is very toxic).

Reduction of Toxicity, Mobility, or Volume Through Treatment.

"This evaluation criterion addresses the statutory preference for selecting remedial actions that employ treatment technologies that permanently and significantly reduce toxicity, mobility, or volume of the hazardous substances as their principal element. This preference is satisfied when treatment is used to reduce the principal threats at a site through destruction of toxic contaminants, reduction of the total mass of toxic contaminants, irreversible reduction in contaminant mobility, or reduction of total volume of contaminated media (EPA/540/G-89/004, 6 - 8)."

This criterion is broken into three sub criteria: amount of hazardous materials (particularly the principal threats) destroyed or treated, degree to which treatment is irreversible, volume reduced, mobility reduced, and toxicity reduced.

> Note: EPA/540/G-89/004 also recommends addressing the type and quantity of treatment residual and statutory preference as a principal element. The issue of residual risk is addressed in the long-term effectiveness measure. Whether the alternative meets statutory preference would be a yes/no value, i.e., either the alternative meets statutory preference or it does not. If the alternative does not meet statutory preference then it receives a value of zero for this CERCLA objective.

- Amount of Principal Threat Treated to Reduce Mobility, Toxicity, or Volume.

This sub criterion satisfies CERCLA's requirement of addressing an alternative's ability to treat hazardous materials, particularly principal threats (EPA/540/G-89/004, 6 - 8).

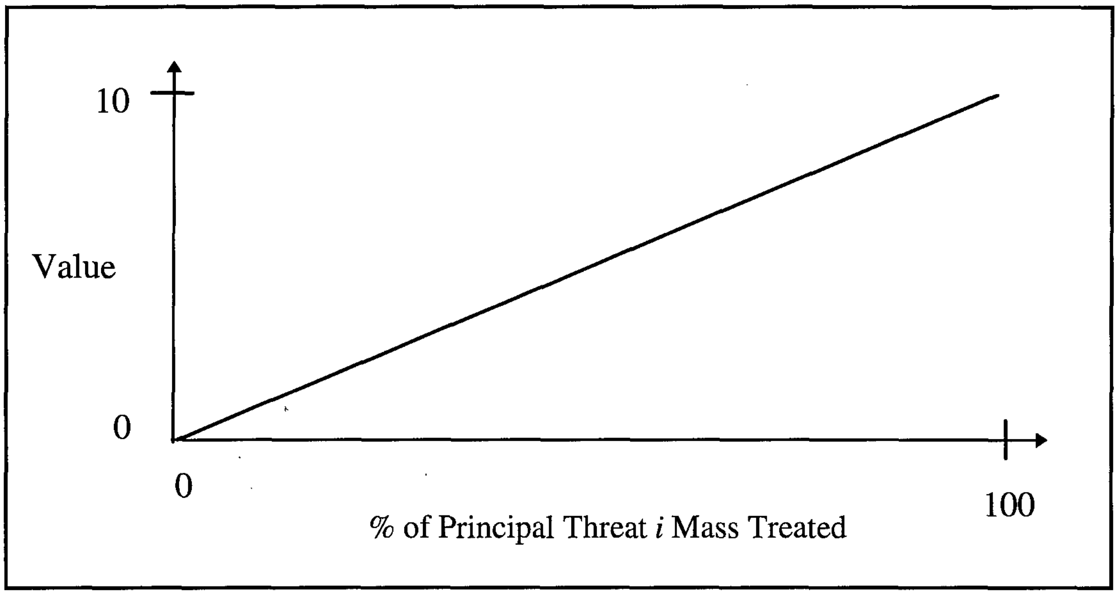


Figure B.12 Amount of principal threats treated measure component value function.

This measures the alternative's ability to treat each type of principal threat. The worst alternative does not treat any of the principal threats and the best alternative treats all of the principal threats. Each alternative receives a value for each category of principal threats. The final value is the average of all of the values across all of the principal threat categories.

- Degree to Which Treatment is Irreversible.

This sub criterion satisfies CERCLA's requirement of addressing the degree to which the treatment is irreversible (EPA/540/G-89/004, 6 - 8).

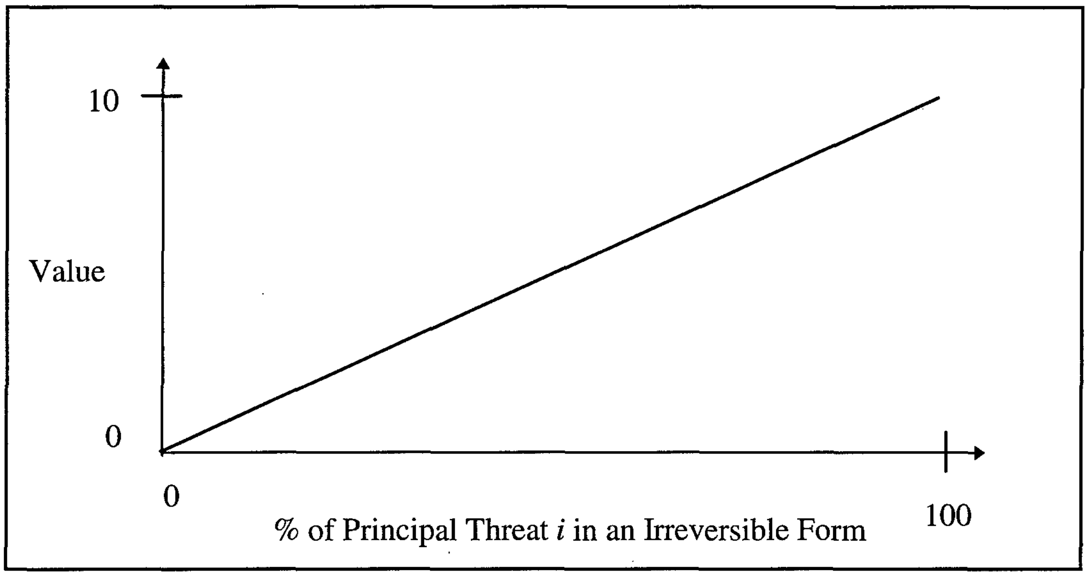


Figure B.13 Degree to which treatment is irreversible measure component value function.

This measure addresses the irreversibility of the treatment. The best alternative leaves all of the principal threats in an irreversible state. Each alternative receives a value for each type of principal threat. The final value is an average of all the values across the categories of principal threats.

Volume Reduced.

This sub criterion is broken into two categories, reduction of volume of the principal threats and the volume of treatment residuals produced during remediation. Although it is not practical to the reduce the actual volume of the principal threats, it is desirable to reduce the volume of the waste media.

Although the volume of treatment residuals produced does not directly relate to volume reduction, it is important parameter to measure. If the treatment process creates a large volume of residual waste (even if the residual waste is not as toxic as the pit waste) problems occur. Not only does the treatment residual need to be disposed of, it must use interim storage space that could be used for pit and trench waste.

- Reduction of Principal Threats Volume

This sub-criterion category satisfies CERCLA's requirement of addressing the degree of expected reduction in volume (EPA/540/G-89/004, 6 - 8).

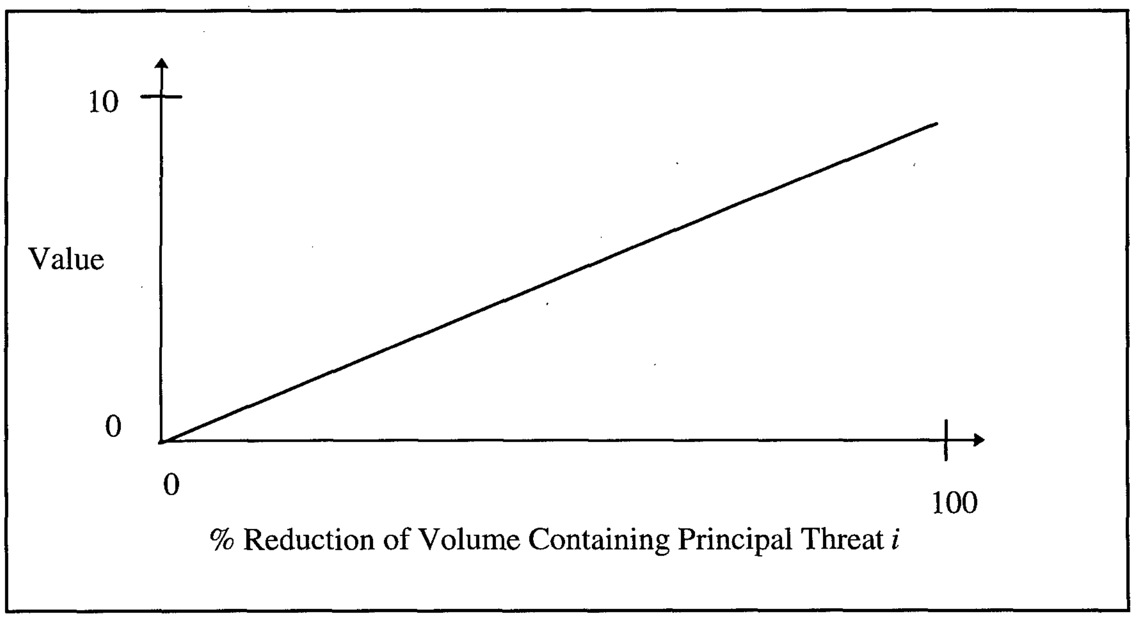


Figure B.14 Reduction of principal threats volume measure component value function.

CERCLA recommends that the degree to which an alternative reduces the volume of principal threats should be measured as a percentage. The percentage reduction used in the x-axis for the above measure is calculated using the equation used below

$$\left[1-\left(\frac{\text{Volume Containing Principal Threat i After Treatment}}{\text{Volume of Media Containing Principal Threat i Before Treatment}}\right)\right]\times 100 .$$

Note: if the volume of the media containing the principal threats is greater after treatment than before treatment then the alternative receives a score of zero for this measure.

- Volume of Treatment Residuals Produced

This sub-criterion category satisfies CERCLA's requirement of addressing the quantity of treatment residuals remaining after treatment (EPA/540/G-89/004, 6 - 8).

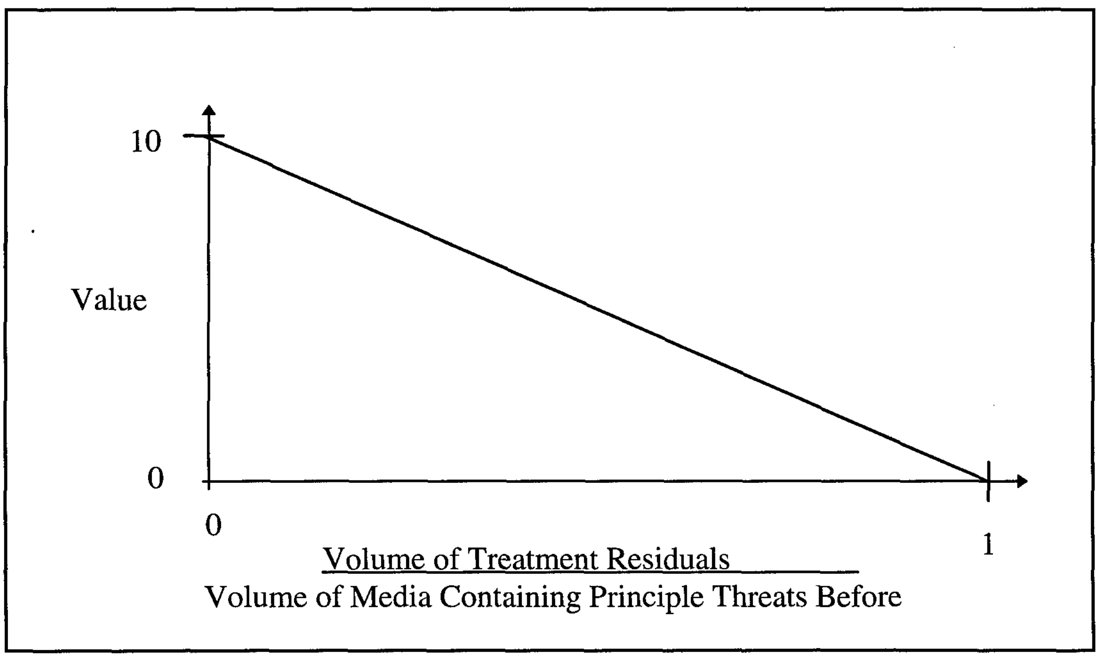


Figure B.15 Volume of treatment residuals produced measure component value function.

This measure ranks the amount of treatment residual from an alternative relative to the volume of the media containing the principal threat. An ideal alternative produces

no residual treatment waste while a bad alternative (for this measure) produces as much or more treatment waste as was originally in the pits and trenches. This treatment residual waste may not be as toxic as the waste, but the residual treatment waste must be disposed, eliminating space for pit and trench waste.

Note: if an alternative has an x-axis score greater than one the alternative receives a value of zero.

- Mobility of Principal Threats Reduced.

The mobility sub criterion is separated into two categories based on the media of concern, air and groundwater. Threat to the air medium is dependent on the flow rates of the principals threats towards the air medium and threat to groundwater is dependent on the principal threat's access towards the groundwater pathway.

- Reduction of Mobility of Principal Threats to Air

This sub - criterion category addresses CERCLA's requirement of addressing the degree of expected reduction of mobility (EPA/540/G-89/004, 6 - 8).

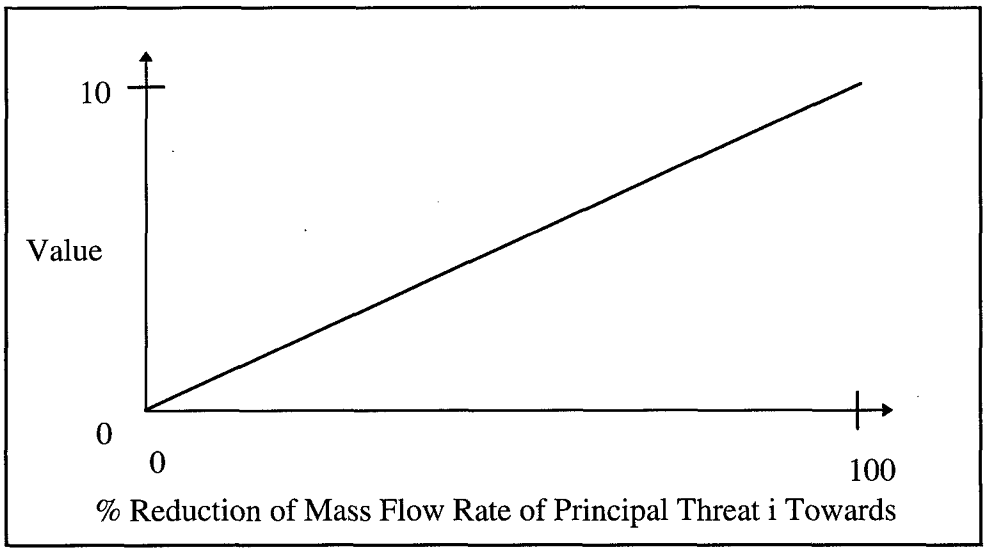


Figure B.16 Reduction of mobility of principal threats to air measure component value function.

The percent reduction of the mass flow rate is calculated using the following equation

$$\left[1-\left(\frac{\text{Mass Flow Rate of Principal Threat i Towards Air After Treatment}}{\text{Mass Flow Rate of Principal Threat i Towards Air Before Treatment}}\right)\right]\times 100.$$

Alternatives receive a value for each category of principal threats. The final value of an alternative is the average across all principal threats.

Note: if the mass flow rate of the principal threats increases after treatment then the alternative receives a value of zero for this measure.

- Reduction of Mobility of Principal Threat to Groundwater

This sub - criterion category also satisfies CERCLA's requirement of addressing an alternative's ability to reduce mobility (EPA/540/G-89/004, 6 - 8).

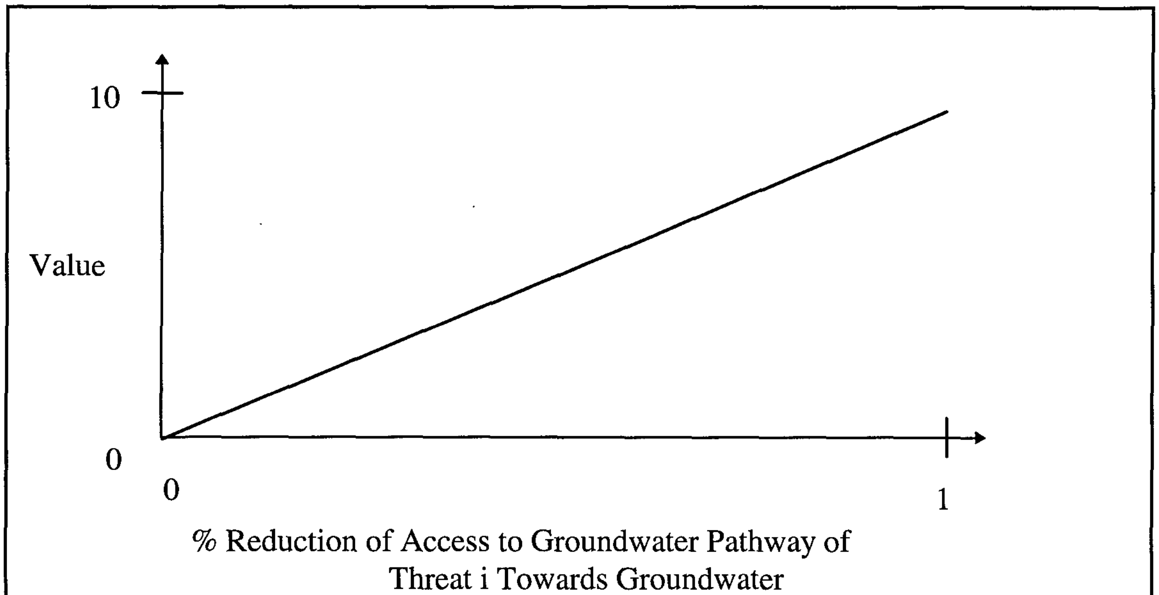


Figure B.17 Reduction of mobility of principal threats to groundwater measure component value function.

The percent reduction of the access toward groundwater pathway is calculated using the following equation

$$\left[1-\left(\frac{\text{Access to Groundwater pathway of Principal Threat i After Treatment}}{\text{Access to Groundwater pathway of Principal Threat i Before Treatment}}\right)\right]\times 100.$$

Alternatives receive a value for each category of principal threats. The final value of an alternative is the average across all principal threats.

Note: if access to the groundwater increases after the treatment then the alternative receives a value of zero for this measure.

- Reduction of Toxicity of Principal Threats (Non-radioactive principal threats).

This sub criterion satisfies CERCLA's requirement of addressing an alternative's ability to reduce the toxicity of principal threats (EPA/540/G-89/004, 6 - 8). This only applies to non-radioactive principal threats because only time can reduce the toxicity of a radioactive waste (radioactive decay).

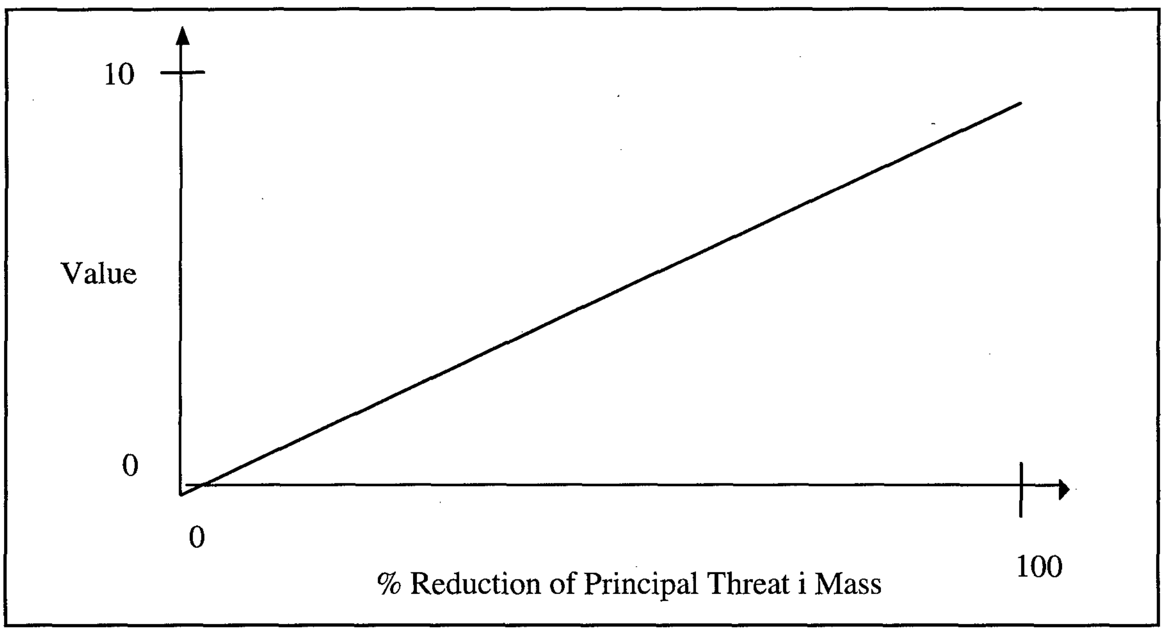


Figure B.18 Reduction of toxicity of principal threats measure component value function.

The toxicity of a principal threat is a function of the toxicity measure and the mass of the principal threat. However, only the mass of the principal threat can be reduced

through treatment. CERCLA recommends reporting this measure as the percent of toxicity reduced. The calculation for the percentage reduction is calculated using the following equation

$$\left[1-\left(\frac{\text{Mass of Principal Threat i After Treat}}{\text{Mass of Principal Threat i Before Treat}}\right)\right]\times 100.$$

Alternatives receive a value for each category of principal threats. The final value of an alternative is the average across all principal threats.

Note: moving the waste from the site and disposing off-site does reduce the mass of the principal threat on-site. However if the alternative does not perform a treatment step, by definition of the reduction of toxicity, mobility, or volume through treatment criterion, the value is zero.

- Cost

CERCLA states this criterion must account for capital cost, operations and management cost, and present worth (EPA/540/G-89/004, 6-10). These three measures are captured in a net present value, NPV.

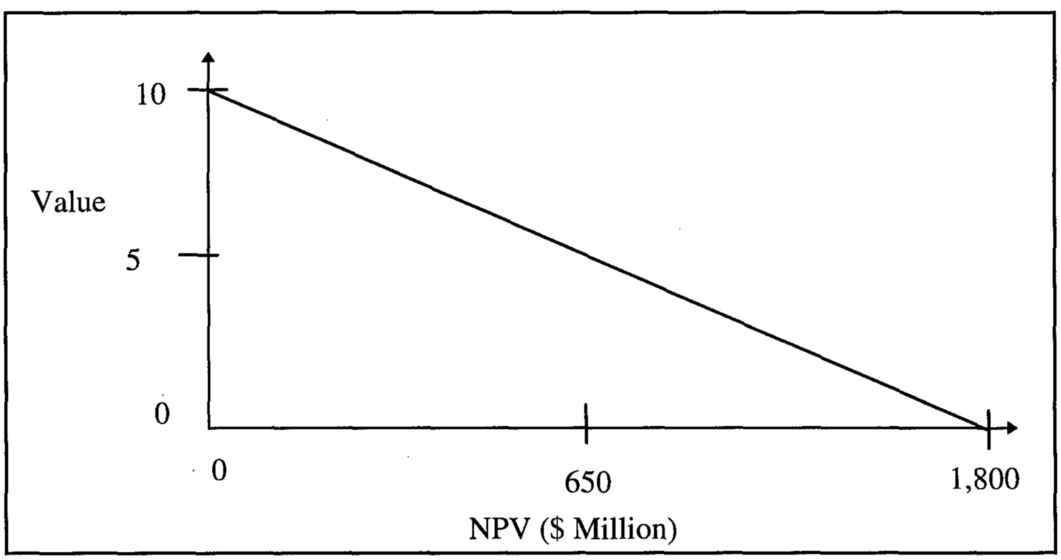


Figure B.19 Cost measure component value function.

Summary of Measures and Explanation of Weights Associated With Each Measure.

CERCLA Criteria Weights

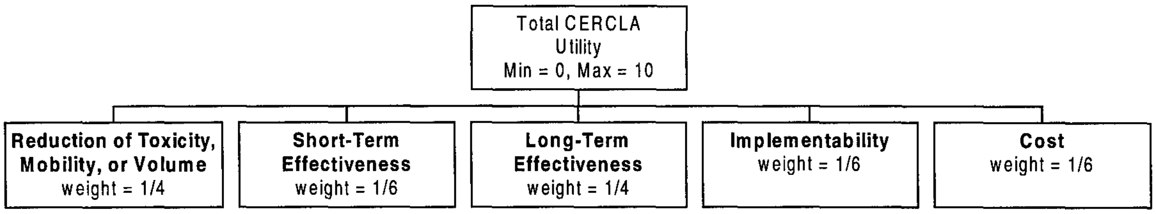


Figure B.20 CERCLA balancing criteria weights.

The sum of the weights of the five CERCLA objectives must equal one. CERCLA states there should be "special emphasis on long-term effectiveness and permanence and reduction of toxicity, mobility, or volume through treatment during the remedy selection (Federal Register, 1990: 8731)." For this reason, the long-term effectiveness and reduction of toxicity, mobility, or volume through treatment criteria were given half of the allowable weight, i.e., the sum of the two criteria weights sum to 1/2. Since CERCLA does not state the relative importance of the emphasis that must be given to the two criteria they are given equal weight, 1/4. The remaining weight (1/2) is split evenly among the three remaining criteria since CERCLA does not state that any criterion is more important than the others. Thus the weight associated with short-term effectiveness, implementability, and cost is 1/6 (1/2 × 1/3).

Implementability Weights

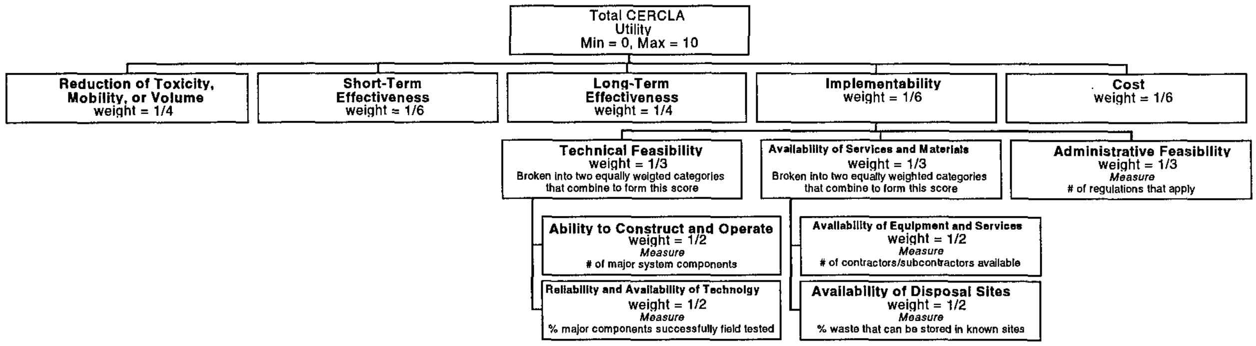


Figure B.21 Implementability criterion measure weights.

The sum of the sub criteria weights under each CERCLA sub criterion must sum to one. Implementability is quantified by three sub criteria: technical feasibility, availability of services and materials, and administrative feasibility. CERCLA does not specify any preference towards any of these measures so all have a weight of 1/3.

Both technical feasibility and availability of services and materials are broken into two categories. In both cases, CERCLA does not specify any preference towards either category so each category has a weight of 1/2.

Short-Term Effectiveness Weights

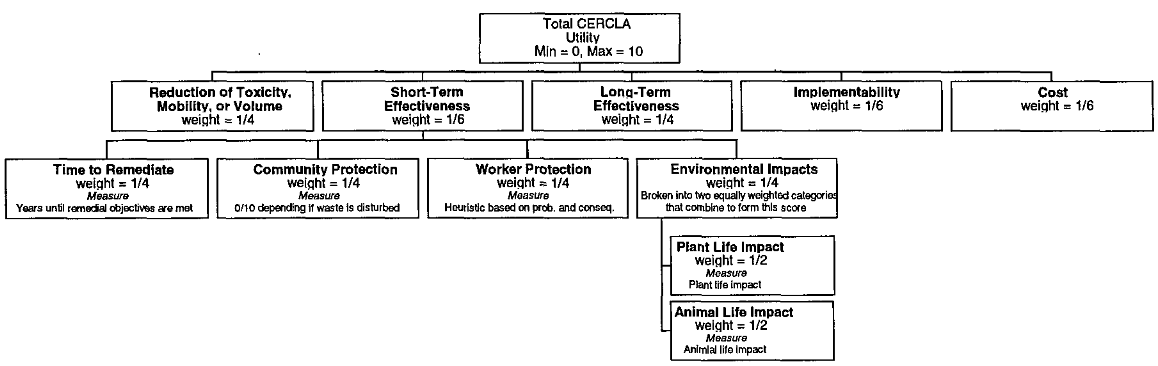


Figure B.22 Short-term effectiveness criterion measure weights.

The short-term effectiveness criterion is quantified by four separate sub criteria: time to remediate, community protection, worker protection, and environmental impacts. Since CERCLA does not state any preference towards any one sub criterion, all have the same weight of 1/4.

The environmental impact sub criterion is separated into two categories: plant impacts and animal impacts. Once again, since CERCLA does not mention any preference towards either category both are equally weighted at 1/2.

Long-Term Effectiveness Weights

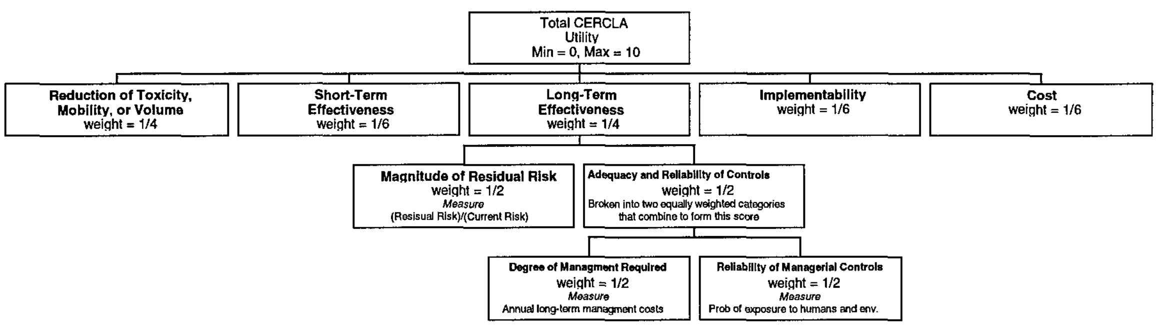


Figure B.23 Long-term effectiveness criterion measure weights.

The long-term effectiveness CERCLA criterion is quantified by two sub criteria: magnitude of residual risk and adequacy and reliability of controls. Both are equally weighted (1/2). Adequacy and reliability of controls is separated into two categories: degree of management required and reliability of managerial controls. Both are given equal weight since CERCLA does not state preference towards either category.

Reduction of Toxicity, Mobility, or Volume Weights

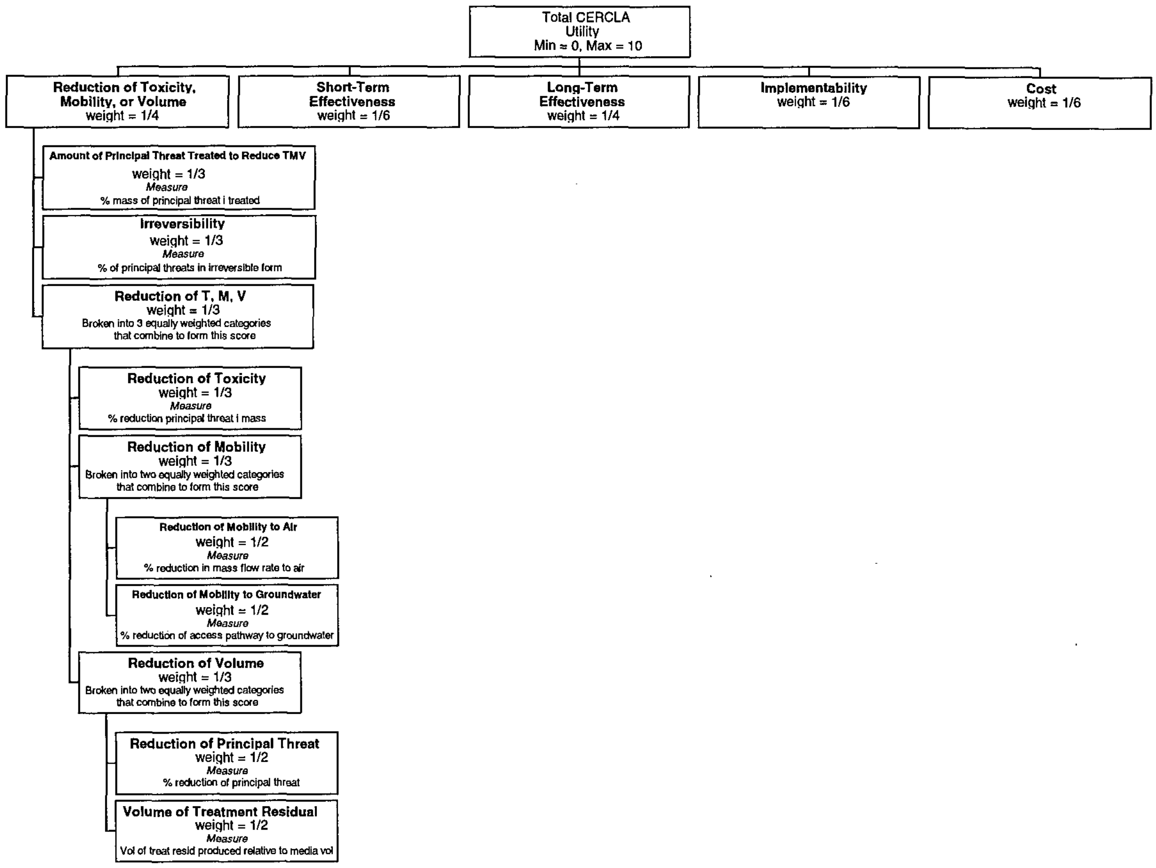


Figure B.24 Reduction of toxicity, mobility, or volume criterion measure weights

Reduction of toxicity, mobility, or volume through treatment is broken into three separate categories: amount of principal threat removed, irreversibility, and reduction of toxicity, mobility, or volume. CERCLA does not state preference towards any of these sub criteria so each receives a weight of 1/3.

The sub criterion reduction of toxicity, mobility, or volume is further broken into three separate categories: reduction of toxicity, reduction of mobility, and reduction of volume. The sum of the weights associated with these categories must equal one. Since CERCLA does not explicitly state a preference towards any of these categories, each has the same weight of 1/3.

Both the reduction of mobility and volume measures are further broken into two separate sub categories. The sum of the weights in each sub category must equal one. In both cases the two sub categories are equally weighted, i.e. 1/2, because CERCLA does not state a preference towards either of the sub categories.

<u>Cost Weight</u>

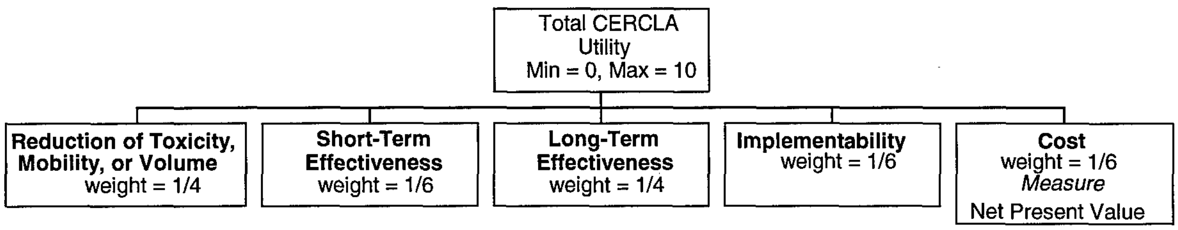


Figure B.25 Cost criterion measure weight.

The cost CERCLA criterion is quantified by only one measure, net present value. Since this is the only measure, it has a weight of one.

Appendix C: SDA Value Function

This appendix provides the additive value function used by both the Logical Decisions and DPL models. In all cases the 'λ' represents the weight associated with the criterion evaluation measure provided by its subscript, the 'v' represents the component value of the criterion provided by its subscript, and the 'x' represents the score associated with train *j* towards the criteria provided in the superscript.

The last part of this section presents an example showing how these equations are used to produce values towards each balancing criterion and an overall value (V) for train 12.

Overall SDA Value Function

$$V(X_j) = \sum_{i-1}^{5} \lambda_i v_i (x_j^i) , \qquad \textbf{(C.1)}$$

where, $V(X_j)$ is the overall value for train *j*'s set of evaluation measure scores, λ_i is the weight associated with the *i*th balancing criterion and $v_i(x_j^i)$ is the train *j*'s value towards the *i*th balancing criterion. The following sections describe the value functions that calculate the balancing criteria values. The table below shows the values associated with each variable in equation C.1.

Table C.1 Variable explanation for equation C.1

i	CERCLA Balancing Criterion	λ_i
1	implementability	1/6
2	short-term effectiveness	1/6
3	long-term effectiveness	1/4
4	reduction of toxicity, mobility or volume through treatment	1/4
5	cost	1/6

Implementability Value Function

Equation C.2 shows the equation used to calculate the implementability (imp) value associated with train *j*.

$$v_{imp}(x_j^{imp}) = \sum_{k=1}^{5} \lambda_{imp}^{k} v_{imp}^{k}(x_j^{imp}), \qquad \textbf{(C.2)}$$

where λ_{imp}^{k} is the weight associated with the *k*th evaluation criterion measure for implementability, and $v_{imp}^{k}(x_j^{imp})$ is the *component* value function associated with the *k*th evaluation criterion measure for implementability. The following table presents the values used for the above equation.

Table C.2 Explanation of variables in equation C.2.

k	criterion evaluation measure	λ_{imp}^{k}	$v_{ste}^{k}(x_j^{ste})$
1	# of major system components	1/6	$v(x) = 10*(0.5)^{x-1}$
2	% of major components successfully deployed in similar media	1/6	$v(x) = 0.1*x$
3	# of contractors/subcontractors willing to place bids	1/6	$v(x) = 2*x$
4	% of waste that can be stored in known and accepted sites	1/6	$v(x) = 0.1*x$
5	Administrative feasibility	1/3	$v(x) = 10 - 0.1*x$

Short-Term Effectiveness Value Function

Equation C.3 shows the equation used to calculate the short-term effectiveness (ste) value associated with train *j*.

$$v_{ste}(x_j^{ste}) = \sum_{k=1}^{5} \lambda_{ste}^{k} v_{ste}^{k}(x_j^{ste}), \qquad \textbf{(C.3)}$$

where λ_{ste}^{k} is the weight associated with the *k*th evaluation criterion measure for short-term effectiveness, and $v_{ste}^{k}(x_j^{ste})$ is the *component* value function associated with the *k*th evaluation criterion measure for short-term effectiveness. The following table presents the values used for the above equation.

Table C.3 Explanation of variables used in equation C.3.

k	criterion evaluation measure	λ_{ste}^{k}	$v_{ste}^{k}(x_j^{ste})$
1	Years before remedial objectives are met	1/4	$v(x) = 10 - 0.45*x \ (x \leq 20)$ $v(x) = 1.101\times10^{-16} + 2.111*e^{-0.03736*x} \ (x > 20)$
2	Community protection heuristic combining risk and level of risk	1/4	$v(x) = x$
3	Worker protection heuristic combining risk and level of risk	1/4	$v(x) = x$
4	Qualitative ranking based on potential harm to animals near SDA	1/8	$v(x) = x$
5	Qualitative ranking based on potential harm to plants near SDA	1/8	$v(x) = x$

Long-Term Effectiveness Utility Function

Equation C.4 shows the equation used to calculate the short-term effectiveness (lte) value associated with train *j*.

$$v_{lte}(x_j^{ste}) = \sum_{k=1}^{3} \lambda_{lte}^{k} v_{lte}^{k}(x_j^{lte}), \qquad \textbf{(C.4)}$$

where λ_{lte}^{k} is the weight associated with the *k*th evaluation criterion measure for long-term effectiveness, and $v_{lte}^{k}(x_j^{lte})$ is the *component* value function associated with the *k*th evaluation criterion measure for long-term effectiveness. The following table presents the values used for the above equation.

Table C.4 Explanation of variables used in equation C.4.

k	criterion evaluation measure	λ_{lte}^{k}	$v_{lte}^{k}(x_j^{lte})$
1	Risk after remediation divided by the current risk	1/2	$v(x) = 10 - 10 * x$
2	Annual long-term management costs	1/4	$v(x) = 10 - 0.02 * x$
3	Probability of exposure from treated residuals and wastes on-site to human and environmental receptors above protective levels	1/4	$v(x) = 10 - 10 * x$

Reduction of Toxicity, Mobility, or Volume Through Treatment Value Function

Equation C.5 shows the equation used to calculate the reduction of toxicity, mobility, or volume through treatment (reduce) value associated with train *j*.

$$v_{reducee}(x_j^{sreduce}) = \sum_{k=1}^{7} \lambda_{reduce}^{k} v_{reduce}^{k}(x_j^{reduce}), \qquad \textbf{(C.5)}$$

where λ_{reduce}^{k} is the weight associated with the *k*th evaluation criterion measure for reduction of toxicity, mobility, or volume through treatment, and $v_{reduce}^{k}(x_j^{reduce})$ is the *component* value function associated with the *k*th evaluation criterion measure for reduction of toxicity, mobility, or volume through treatment. The following table presents the values used for the above equation.

Table C.5 Explanation of variables used in equation C.5.

k	criterion evaluation measure	λ_{reduce}^{k}	$v_{reduce}^{k}(x_j^{reduce})$
1	Percent mass of principal threats treated	1/3	v(x) = 0.1 * x
2	Percent of principal threats in an irreversible form	1/3	v(x) = 0.1 * x
3	Percent reduction in principal threat mass flow rates towards air	1/18	v(x) = 0.1 * x
4	Percent reduction of principal threat access to groundwater	1/18	v(x) = 0.1 * x
5	Percent reduction in volume containing principal threats	1/18	v(x) = 0.1 * x
6	Volume of treatment residuals produced by volume of media containing principal threats	1/18	v(x) = 10 - 0.1 * x
7	% reduction of principal threat mass	1/9	v(x) = 0.1*x

Cost Value Function

There is only one measure quantifying a train's performance for the cost balancing criterion, net present value. Hence

$$v_{cost}(x_j) = 10 - 5.425 \times 10^{-6} x_j, \qquad \textbf{(C.6)}$$

where x_j is the net present value of train *j*.

Example Calculations

The remainder of this appendix provides an example calculation for each CERCLA balancing criterion and the overall value for train 12 with the following scores.

Table C.6 Weights scores and Scores associated with train 12.

SDA Criterion	λ_k	*Score (x_{12})*	*Measure Component Value Function*	*Comp Value*
IMPLEMENTABILITY	**1/6**			
Technical Feasibility (2 measures)				
Ability to construct and operate	1/6	4	$v(x) = 10*(0.5)^{x-1}$	1.25
Reliability and availability	1/6	100	$v(x) = 0.1*x$	10
Availability of Services and Materials (2 measures)				
Availability of equipment and services	1/6	5	$v(x) = 2*x$	10
Availability of storage and disposal services	1/6	100	$v(x) = 0.1*x$	10
Administrative feasibility	1/3	10	$v(x) = 10 - 0.1*x$	9
SHORT-TERM EFFECTIVENESS	**1/6**			
Time to remediate	1/4	10	$v(x) = 10 - 0.45*x$ when $x \leq 20$ $v(x) = -1.11\times10^{-6}$ $+2.11*\exp(0.03736*x)$ when $x > 20$	5.5
Community protection	1/4	6	$v(x) = x$	6
Worker protection	1/4	8.4	$v(x) = x$	8.4
Environmental Impacts (2 measures)				
Animal impact	1/8	0	$v(x) = 10 - x$	10
Plant impact	1/8	0	$v(x) = 10 - x$	10
LONG-TERM EFFECTIVENESS	**1/4**			
Magnitude of residual risk	1/2	.45	$v(x) = 10 - 10*x$	5.5
Adequacy and Reliability of Controls (2 measures)				
Degree of management required	1/4	393*	$v(x) = 10 - 0.02*x$	2.14
Reliability of managerial controls	1/4	0.4	$v(x) = 10 - 10*x$	6
REDUCTION OF TMV THROUGH TREATMENT	**1/4**			
Amount of principal threats treated	1/3	17	$v(x) = 0.1*x$	1.7
Irreversibility of treatment	1/3	17	$v(x) = 0.1*x$	1.7
Reduction of TMV (1 measure, 2 categories)				
Reduction of toxicity	1/9	50	$v(x) = 0.1*x$	5
Reduction of mobility *(2 sub categories)*				
Reduction of mobility towards air	*1/18*	75	$v(x) = 0.1*x$	7.5
Reduction of mobility towards groundwater	*1/18*	17	$v(x) = 0.1*x$	1.7
Reduction of volume *(2 sub categories)*				
Reduction of principal threat volumes	*1/18*	30	$v(x) = 0.1*x$	3
Volume of treatment residuals	*1/18*	0	$v(x) = 10 - 10*x$	10
COST	**1/6**	127,040	$v(x) = 10 - 5.425\times10^{-6}*x$	9.311

* The scores for the degree of management required and cost measures are in dollars divided by 1000

Table C.6 provides weights associated with criterion level and the evaluation measure scores, component value functions, and component values for each measure. These values are combined using the additive value function provided by equation C.1 to calculate the value for the five balancing criteria and the overall value for train 12. One can verify that the models produced the scores shown below by comparing to the values to those in Table K.1

Implementability Value

$v_{imp}(x_{12}^{imp}) = 1/6\times1.25 + 1/6\times10 + 1/6\times10 + 1/6\times10 + 1/3\times9 = \mathbf{8.208}$.

Short-Term Effectiveness

$v_{ste}(x_{12}^{ste}) = 1/4\times5.5 + 1/4\times6 + 1/4\times8.4 + 1/8\times10 + 1/8\times10 = \mathbf{7.475}$.

Long-Term Effectiveness

$v_{lte}(x_{12}^{lte}) = \mathbf{1/2}(5.5) + \mathbf{1/2}(1/2 \times 2.14 + 1/2 \times 6) = \mathbf{4.785}$.

Reduction of Toxicity, Mobility, or Volume Through Treatment

$v_{reduce}(x_{12}^{reduce}) = 1/3\times1.7 + 1/3\times1.7 + 1/18\times7.5 + 1/18\times1.7 + 1/18\times3 + 1/18\times10 + 1/9\times5 = \mathbf{2.922}$

Cost

$v_{cost}(x_{12}^{cost}) = 9.311$ (There is only one measure for cost, net present value.)

Overall Value

Overall value is simply the sum of all of the weights associated with each CERCLA balancing criterion and its associated value as shown below.

$v_{12}(X) = \mathbf{1/6} \times 8.208 + \mathbf{1/6} \times 7.475 + \mathbf{1/4} \times 4.785 + \mathbf{1/4} \times 2.922 + \mathbf{1/6} \times 9.311 = 6.093$

Appendix D: Logical Decisions Model

Logical Decisions is a commercial software package using decision analysis techniques to provide insight into the desirability of a set of alternatives and help decisionmakers think through difficult choices in a logical way (Logical Decisions, 1995; 23). Logical Decisions was selected for use in this analysis because it evaluates alternatives through the same value-focused thinking and multiattribute preference theory techniques used in the SDA remediation strategy selection process. Logical Decisions uses four types of interlinked objects to evaluate and rank strategies. These objects are listed and described below (Logical Decisions, 1995: 15):

1. **Measures**. Measures are variables describing the performance of alternatives towards the decisionmakers' goals.
2. **Goals**. Goals are containers holding measures and other goals. Goals are not quantified directly. Logical Decisions uses an alternative's performance on the measures and sub-goals under a goal to infer its performance on the goal itself. Logical Decisions helps the user arrange the goals and measures into a fundamental objectives hierarchy.
3. **Preference Sets**. Preference sets contain the value judgments needed to rank the strategies based on the measures and goals. Preference sets contain component value functions that convert measure values into component value. Preference sets also contain weights associated with each measure and goal, allowing Logical Decisions to combine the component values associated with evaluation measure scores into values for the various goals.

Clearly, the objects associated with the Logical Decisions software are consistent with the value-focused thinking and multiattribute preference theory techniques used in this research. The SDA hierarchy and weights are shown in figure D.1. The measures, and component value functions from Appendix B were entered into the Logical Decisions. These inputs are summarized in Table D.1. Clearly, these are the exact same hierarchy, weights, and functions presented previously in this section. In addition, the remedial strategies and the evaluation measure scores associated with each strategy (from Appendix I) were entered into the program.

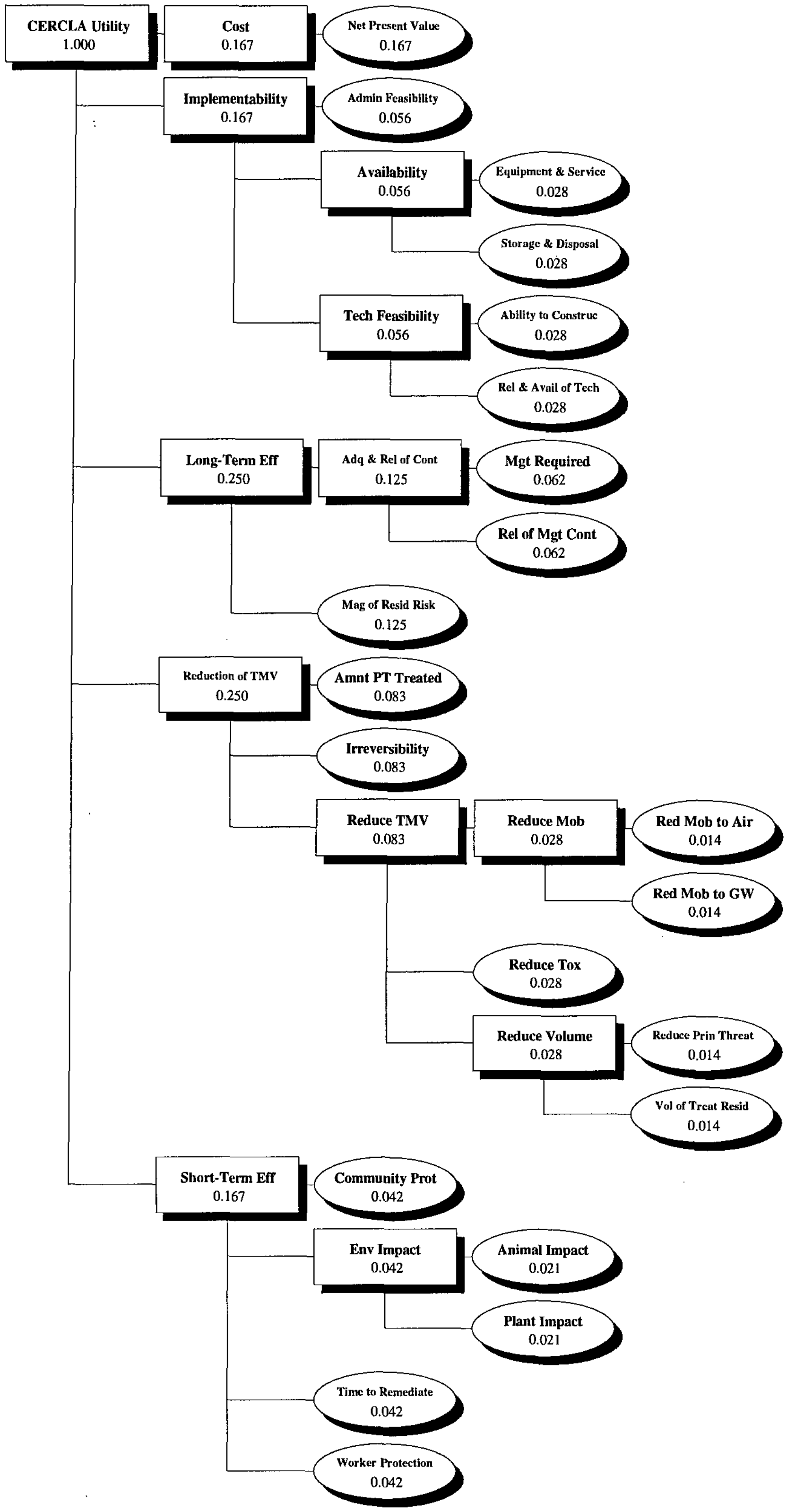


Figure D.1 Logical Decisions hierarchy and overall weights for the SDA decisionmakers.

Table D.1 Criterion measures and value functions entered into Logical Decisions.

Range		Midpoint		SUF Parameters		
Minimum	Maximum	Level	Utility	a	b	c
Ability to Const						
0	1	0.5	0.5625	1.25	8.75	0
1	2	1.5	0,75	15	-5	0
2	3	2.5	0.375	10	-2.5	0
3	4	3.5	0.1875	6.25	-1.25	0
4	5	4.5	0.09375	3.75	-0.625	0
5	6	5.5	0.04688	2.188	-0.3125	0
6	7	6.5	0.02344	1.25	-0.1562	0
7	9	8	0.009768	0.5663	-0.05858	0
9	10	9.5	0.002929	0.2148	-0.01953	0
10	11	10.5	0.001465	0.1171	-0.00976	0
11	33	22	0.0004885	0.01465	-0.0004441	0
33	36	34.5	0	0	0	0
36	42	39	0	0	0	0
Rel & Avail of Tech						
0	100	50	0.5	0	0.1	0
Equipment & Service						
0	5	2.5	0.5	0	2	0
Storage & Disposal						
0	100	50	0.5	0	0.1	0
Admin Feasibility						
0	100	50	0.5	10	-0.1	0
Time to Remediate						
0	20	10	0.55	10	-0.45	0
20	1000	46.67	0.03692	-1.106e-16	2.111	0.03736
Worker Protection						
9.6	10	9.8	0.98	0	1	0
8.8	9.6	9.2	0.92	0	1	0
8	8.8	8.4	0.84	0	1	0
7.6	8	7.8	0.78	0	1	0
7.2	7.6	7.4	0.74	0	1	0
6.4	7.2	6.8	0.68	0	1	0
2	6.4	4.2	0.42	0	1	0
0	2	1	0.1	0	1	0
Community Prot						
0	10	5	0.5	0	1	0
Plant Impact						
1	2	1.5	0.5	20	-10	0
Animal Impact						
1	2	1.5	0.5	20	-10	0
Mag of Resid Risk						
0	1	0.5	0.5	10	-10	0
Mgt Required						
0	500	250	0.5	10	-0.02	0
Rel of Mgt Cont						
0	1	0.5	0.5	10	-10	0
Amnt PT Treated						
0	100	50	0.5	0	0.1	0
Irreversibility						
0	100	50	0.5	0	0.1	0
Reduce Tox						
0	100	50	0.5	0	0.1	0
Red Mob to Air						
0	100	50	0.5	0	0.1	0
Red Mob to GW						
0	100	50	0.5	0	0.1	0
Reduce Prin Threat						
0	100	50	0.5	0	0.1	0
Vol of Treat Resid						
0	1	0.5	0.5	10	-10	0
Net Present Value						
0	1.843e+06	9.217e+05	0.5	10	-5.425e-06	0

SUF Parameters: if c = 0, U(x) = a + bx, if c # 0, U(x) = a + b(EXP(-cx))

Appendix E: Comments for Logical Decisions Model

CERCLA Value Goal:

Comprehensive Environmental Restoration Compensation and Liability Act. The strategic objective of the decisionmakers.

Reduction of TMV Goal:

Reduction of Toxicity, Mobility, or Volume Through Treatment is a main CERCLA criterion. This criterion is broken into three sub criteria that are further broken into three categories. Two of the three categories are further broken into equally weighted sub categories.

Short-Term Eff Goal:

The Short-Term Effectiveness CERCLA criterion is broken into four equally weighted sub criteria. One sub criterion is further broken into two equally weighted categories.

Long-Term Eff Goal:

Long-Term Effectiveness is a main criterion of CERCLA. This criterion is broken into two equally weighted sub criteria: Magnitude of Residual Risk and Adequacy and Reliability of Controls. The later is further broken into two equally weighted categories.

Implementability Goal:

This is a main criterion of CERCLA. Implementability is further broken into three equally weighted sub criteria. Two of these sub criteria are further broken into two equally weighted categories.

Cost Goal:

This is a main CERCLA criterion.

Availability Goal:

The Availability of Services and Materials sub criterion is broken into two equally weighted categories: Availability of Necessary Equipment and Specialists and Prospective Technologies and Availability of Disposal Sites.

Tech Feasibility Goal:

The Technical Feasibility sub criterion of Implementability is broken into two equally weighted categories: Ability to Construct and Operate the Technology and Reliability and Availability of the Technology.

Adq & Rel of Cont Goal:

The Adequacy and Reliability of Controls sub criterion is broken into two equally weighted categories: Degree of Management Required and Reliability of Managerial Controls.

Reduce TMV Goal:

The Reduction of Toxicity, Mobility, or Volume Through Treatment sub criterion is broken into three equally weighted categories: Reduction of Toxicity, Reduction of Mobility, and Reduction of Volume.

Reduce Mob Goal:

The Reduction of Mobility category is further broken into two equally weighted sub categories: Reduction of Mobility Towards Air Medium and Reduction of Mobility Towards Groundwater Medium.

Reduce Volume Goal:

The Reduction in Volume category is further broken into two equally weighted sub categories: Reduction of Principal Threat Volume and Volume of Treatment Residuals.

Env Impact Goal:

The Environmental Impact sub criterion is broken into two equally weighted categories: Animal Impact and Plant Impact.

Comments for Measures

Net Present Value Measure:

This is the one and only measure for the cost criterion. The measure is net present value in billions of dollars. Data for this measure is supplied by MSE.

Admin Feasibility Measure:

The measure for the administrative feasibility sub criterion is the % of the regulations that must be applied relative to the Train 25. This measure will eventually be replaced by the actual number of regulations that will apply.

Mag of Resid Risk Measure:

The Magnitude of Residual Risk is measured by the Risk of the Site After Remediation/Risk of the Site Prior to Remediation.

Amnt PT Treated Measure:

The Amount of Principal Threat Treated sub criterion is measured by the Percentage of Principal Threats Treated.

Irreversibility Measure:

The Irreversibility sub criterion is measured by the Percentage of Principal Threats in Irreversible Form.

Time to Remediate Measure:

The Time to Remediate sub criterion is measured by the Number of Years a Technology Needs to Meet Remediation Objectives.

Community Prot Measure:

The Community Protection sub criterion is measured through a heuristic similar to the one created by John Richardson and John Nonte of INEEL for worker protection. The heuristic combines the relative probability of an occurrence and the consequence associated with the occurrence to produce the score.

Equipment & Service Measure:

The Availability of Necessary Equipment and Specialists and Prospective Technologies category is measured by the # of contractors or subcontractors willing to place a bid. Either contractors or subcontractors is used depending on which is the limiting factor.

Storage & Disposal Measure:

The Availability of Storage and Disposal Services category is measured by the % of waste that can be stored in known and acceptable sites.

Ability to Construc Measure:

The Ability to Construct and Operate category is measured by the # of major system components associated with a strategy.

Rel & Avail of Tech Measure:

The Reliability and Availability of the Technology category is measured by the percent of system components successfully deployed in a similar media.

Mgt Required Measure:

The Degree of Management Required is measured through the amount that will be spent (in millions) on annual long-term managerial costs associated with a technology once it is implemented. Note: this is the actual projected annual cost. It is NOT a cumulative total discounted over time. Data for this measure is supplied by MSE.

Rel of Mgt Cont Measure:

The Reliability of Managerial Controls sub criterion is measured by the Probability of Exposure from Treated Residuals and Wastes On-Site to Human and Environmental Receptors Above Protective Levels.

Reduce Tox Measure:

The Reduction of Toxicity category is measured by the Percent Reduction of Principal Threat Mass.

Red Mob to Air Measure:

The Reduction of Mobility Towards the Air sub category is measured by the Percent Reduction in the Mass Flow Rate of the Principal Threats Towards the Air Medium.

Red Mob to GW Measure:

The Reduction of Mobility Towards Groundwater Medium sub category is measured by the Percent Reduction in Access Towards Groundwater.

Reduce Prin Threat Measure:

The Reduction in Principal Threats sub category is measured by the Percent Reduction of Media Containing the Principal Threats.

Vol of Treat Resid Measure:

The Volume of Treatment Residuals sub category is measured by the Volume of Residuals/Volume of Media Containing the Principal Threats Prior to Remediation.

Plant Impact Measure:

The Plant Impact category is measured through labels. The more rare/endangered the plant species affected by a technology, the lower the score.

Animal Impact Measure:

The Animal Impact category is measured through labels. The more rare/endangered the animal species affected by a technology, the lower the score.

Worker Protection Measure:

The Worker Protection sub criterion is measured through a heuristic created by John Richardson and John Nonte of INEEL. The heuristic combines the relative probability of an occurrence and the consequence associated with the occurrence to produce the score.

Appendix F: DPL Model

Figure F.1 shows the DPL influence diagram used in this analysis. This figure shows how all of the CERCLA balancing criteria values are modeled and then combined to provide an overall value. Figures F.2 - F.5 show how each of the balancing criteria are modeled (the cost criterion model is not shown because it consists of only one measure). Finally, figure F.6 shows how the overall value is modeled.

In figure F.1 the rectangle represents the decision facing the decisionmakers at INEEL, determining the best remediation strategy. The rounded rectangles (value nodes), with arrows going into them, represent the CERCLA criterion measure scores associated with each alternative. The value nodes to the right of the scores represent the value associated with each score. The value nodes to the far right of the measure scores represent the weights associated with each measure. The five right-most value nodes of the diagram are the weights associated with each of the five balancing CERCLA criteria. Finally, all of the CERCLA criteria utility values and weights have arrows leading into to the "Total CERCLA Value" node.

Recall, from Chapter Two, that arrows represent influence from the originating node to the destination node. Thus, one can clearly see by the influence diagram (in figure F.2) that the strategy affects the scores associated with each balancing CERCLA criterion evaluation measure. The measures quantifying each CERCLA criterion and the associated weights are combined to form values for each of the balancing CERCLA criteria. Finally, the five balancing criteria values are multiplied by their respective weights to an overall value for that alternative.

The criteria weights, component value functions, and overall value functions presented in Appendix B were entered into DPL to create an SDA selection model. As the influence diagram shows, DPL calculates the value for each of the five balancing CERCLA criteria for each alternative using the additive value functions presented in Appendix C. DPL stores these CERCLA criteria utilities as five different attributes in DPL. DPL calculates the overall value through the additive value function presented in equation 3.1. Keeping the balancing CERCLA criteria as separate attributes allows the decisionmakers to see how well an alternative performs in all five balancing criteria rather than overall value alone.

In addition to the model parameters, 567 value nodes containing the data associated with each strategy's value for all 21 measures are entered into the DPL model. These value nodes are connected to an EXCEL spreadsheet containing all of the measure scores for each strategy. Appendix I provides the actual data contained in the spreadsheet.

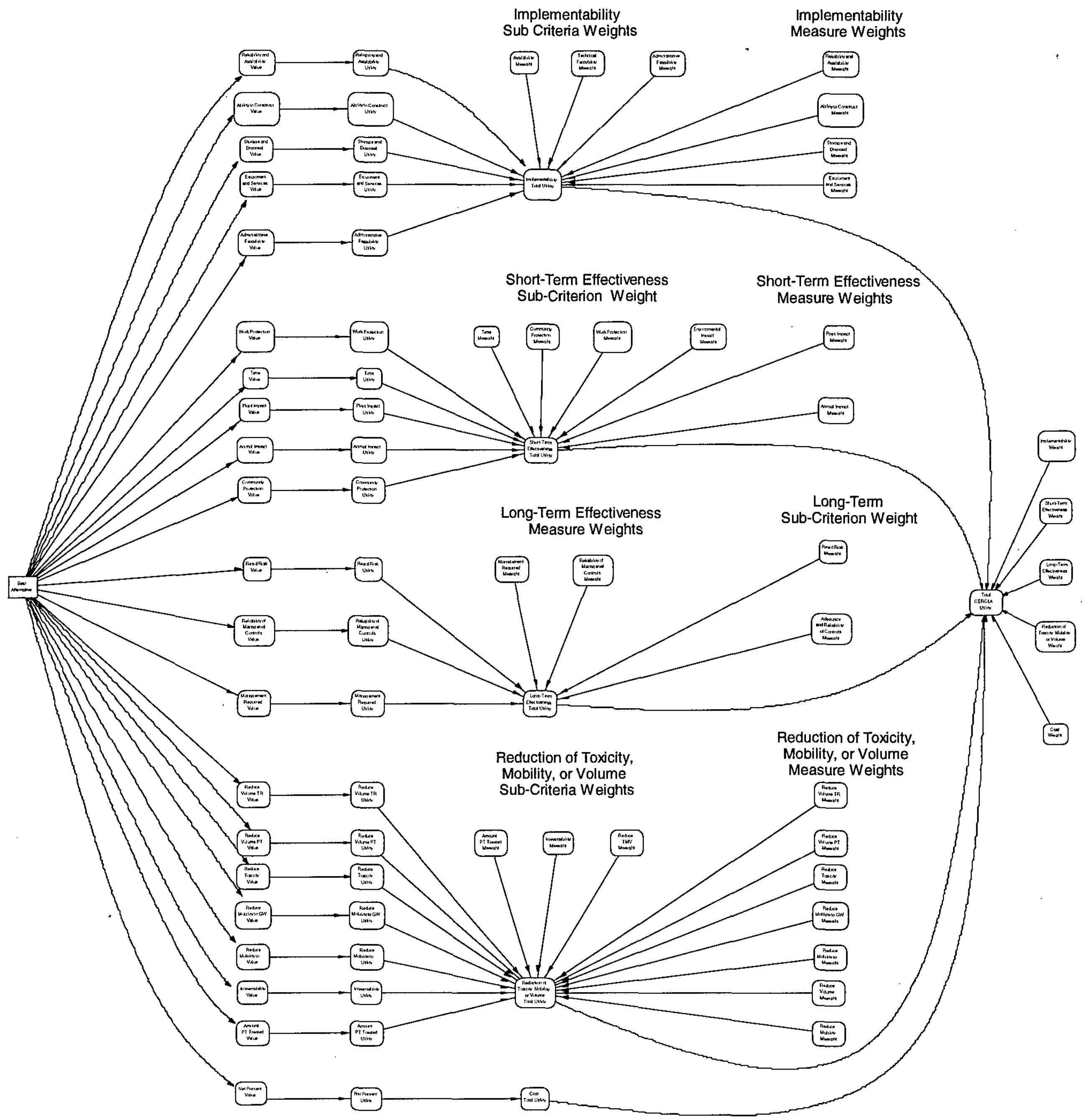


Figure F.1 DPL influence diagram for the SDA remediation strategy selection decision.

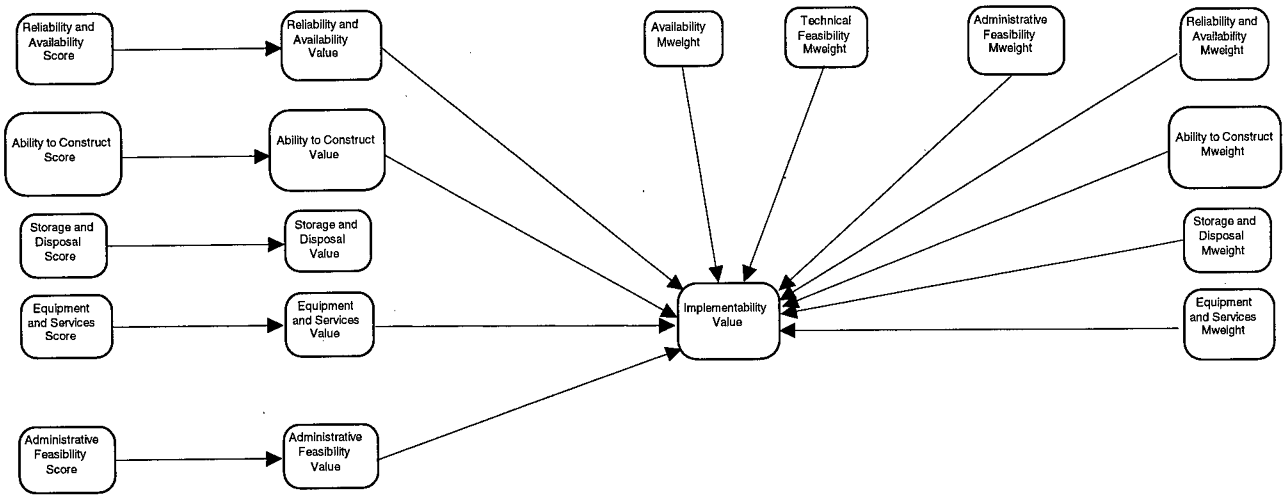


Figure F.2 Implementability CERCLA balancing criteria model.

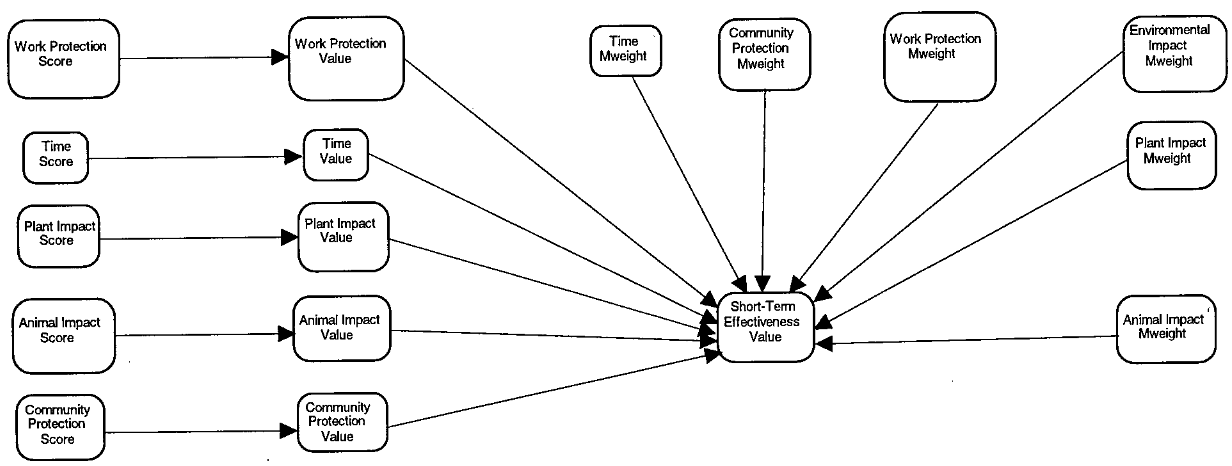


Figure F.3 Short-term effectiveness CERCLA balancing criteria model.

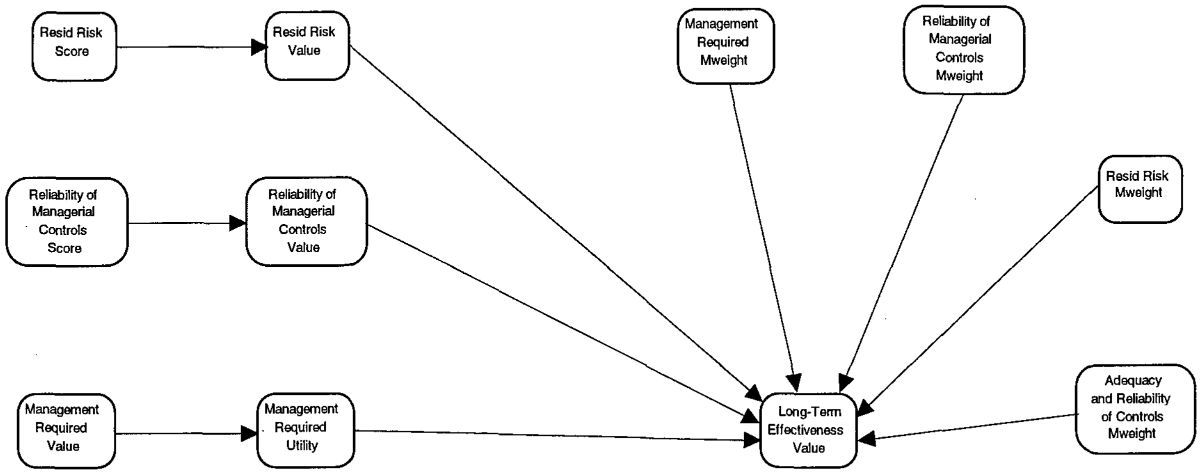


Figure F.4 Long-term effectiveness CERCLA balancing criterion model.

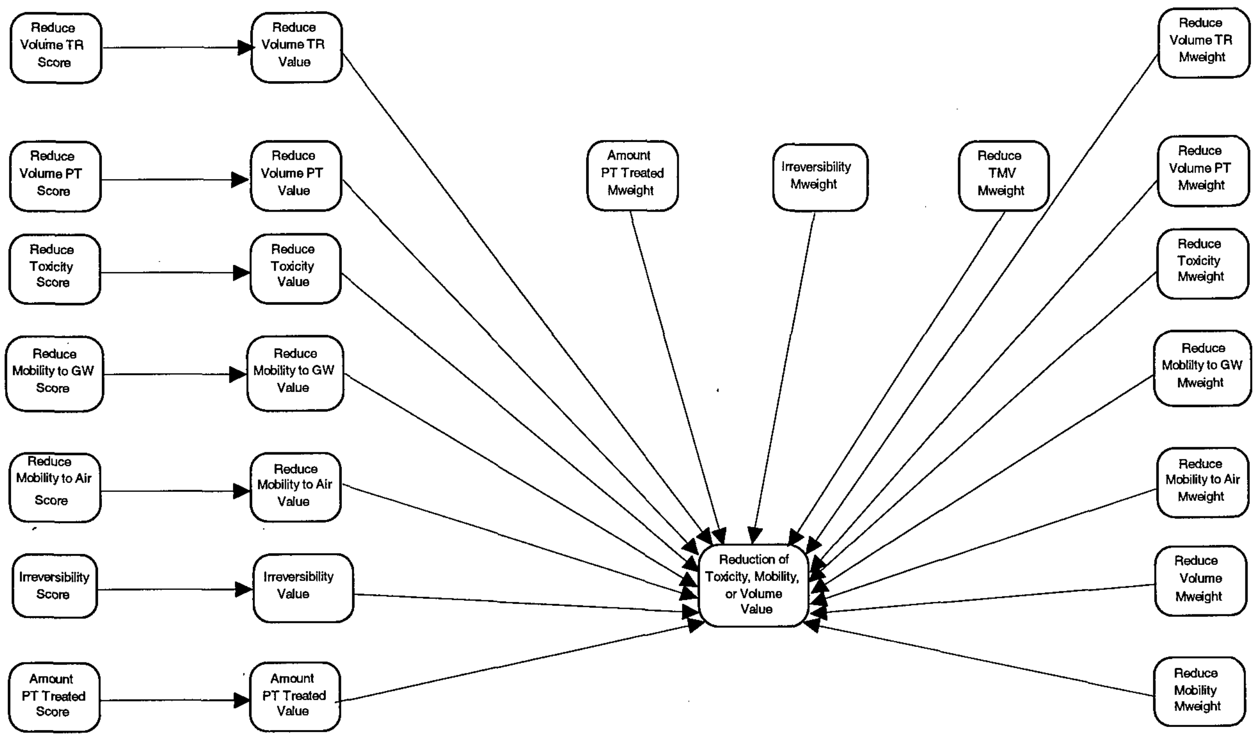


Figure F.5 Reduction of toxicity, mobility, or volume through treatment CERCLA balancing criterion model.

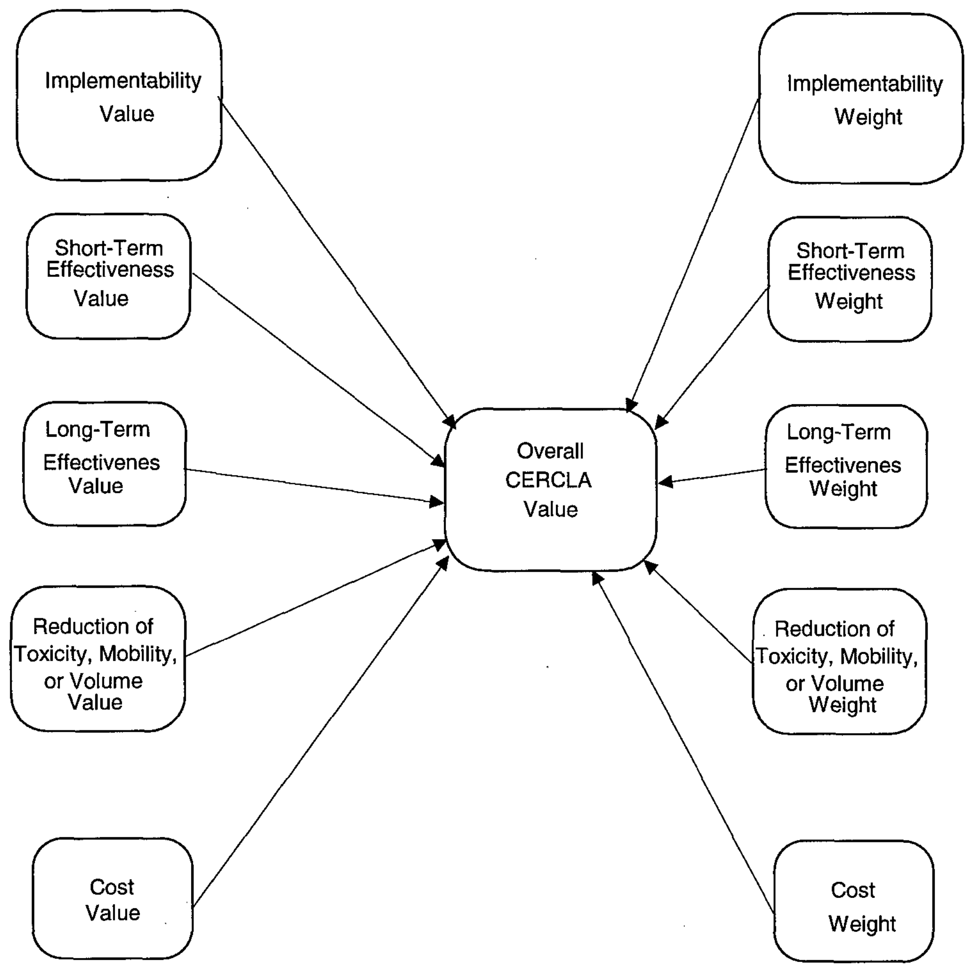


Figure F.6 Overall value model.

Appendix G: Comments From DPL Nodes.

Decision: Best Alternative

The only decision node in the model, The Best Alternative choice determines the values for each of the 21 measures associated with all 28 alternative trains. The values associated with each measure are linked to an EXCEL spreadsheet. The spreadsheet contains variables in the form 'tX_Y' where the X represents the train # and Y is the measure. The table below shows the measures associated with each Y value.

Y	Criteria With an Evaluation Measure
1	Ability to Construct and Operate
2	Reliability and Availability
3	Availability of Equipment and Services
4	Availability of Storage and Disposal Services
5	Administrative Feasibility
6	Time Until Remedial Objectives Are Met
7	Community Protection
8	Worker Protection
9	Environmental Impact on Plants
10	Environmental Impact on Animals
11	Magnitude of Residual Risk
12	Degree of Management Required
13	Reliability of Managerial Controls
14	Amount of Principal Threats Treated
15	Irreversibility
16	Reduction in Volume of Principal Threats
17	Volume of Treatment Residuals
18	Reduction of Mobility Towards Air
19	Reduction of Mobility Towards Groundwater
20	Reduction of Toxicity
21	Cost

For example 't1_1' is the score associated with train l's Ability to Construct and Operate measure.

Value: Implementability Value

Implementability is a CERCLA Criterion. The criterion is further broken into three equally weighted sub criteria, Two of these sub criteria are further broken into two equally weighted categories.

Value: Administrative Feasibility Mweight

Weight associated with the Administrative Feasibility sub criterion under Implementability.

Value: Equipment and Services Mweight

Weight associated with the Availability of Equipment and Services category,

Value: Storage and Disposal Mweight

Weight associated with the Availability of Storage and Disposal Services category.

Value: Ability to Construct Mweight

Weight associated with the Ability to Construct category.

Value: Reliability and Availability Mweight

Weight associated with the Reliability and Availability of Technology category,

Value: Availability Mweight

Weight associated with the Availability of Services and Materials sub criterion under Implementability, This sub criterion is broken into two equally weighted categories: Availability of Equipment and Services and Availability of Disposal Services.

Value: Technical Feasibility Mweight

Weight associated with the Technical Feasibility sub criterion under Implementability. This sub criterion is broken into two equally weighted categories: Ability to Construct and Operate and Reliability and Availability of the Technology.

Value: Community Protection Mweight

Weight associated with the Community Protection sub criterion.

Value: Animal Impact Mweight

Weight associated with the Animal Impact category.

Value: Plant Impact Mweight

Weight associated with the Plant Impact category.

Value: Time Mweight

Weight associated with the Time Until Remediation Objectives are Achieved sub criterion,

Value: Work Protection Mweight

Weight associated with the Worker Protection sub criterion.

Value: Short-Term Effectiveness Value

Short-Term Effectiveness is a CERCLA Criterion. This criterion is broken into four equally weighted sub criteria. One sub criterion is further broken into two equally weighted categories.

Value: Environmental Impact Mweight

Weight associated with the Environmental Impact sub criterion, This sub criterion is broken into two equally weighted categories: Plant Impact and Animal Impact.

Value: Overall CERCLA Value

This node is used only for visual aid purposes to show that all of the utility scores for each of the five balancing CERCLA criteria are combined to form an overall CERCLA value. The actual calculation of the value is performed by the DPL objective function.

Value: Management Required Mweight

Weight associated with the Degree of Management Required Category.

Value: Reliability of Managerial Controls Mweight

Weight associated with the Reliability of Managerial Controls category.

Value: Residual Risk Mweight

Weight associated with the Magnitude of Residual Risk sub criterion under Long-Term Effectiveness.

Value: Long-Term Effectiveness Value

Long-Term Effectiveness is a CERCLA criterion, The criterion is broken into two equally weighted sub criteria. One sub criterion is broken into two equally weighted categories.

Value: Adequacy and Reliability of Controls Mweight

Weight associated with the Adequacy and Reliability of Controls sub criterion under Long-Term Effectiveness. The sub criterion is broken into two equally weighted categories: Degree of Management Required and Reliability of Managerial Controls.

Value: Implementability MWeight

Weight associated with the Implementability criterion.

Value: Short-Term Effectiveness Weight

Weight associated with the Short-Term Effectiveness criterion.

Value: Long-Term Effectiveness Weight

Weight associated with the Long-Term Effectiveness criterion.

Value: Reduction of Toxicity, Mobility, or Volume Weight

Weight associated with the Reduction of Toxicity, Mobility, or Volume Through Treatment criterion.

Value: Cost Weight

Weight associated with the Cost criterion,

Value: Amount PT Treated Mweight

Weight associated with the Amount of Principal Threats Treated sub criterion.

Value: Reduction of Toxicity, Mobility, or Volume Value

Reduction of Toxicity, Mobility, or Volume is a CERCLA criterion. This criterion is broken into three equally weighted criteria, One sub criterion is further broken into three equally weighted categories. Finally, two of the categories are both further broken into two equally weighted sub categories.

Value: Irreversibility Mweight

Weight associated with the Irreversibility sub criterion.

Value: Reduce Mobility to Air Mweight

Weight associated with the Reduction of Mobility Towards Air sub category.

Value: Reduce Mobility to GW Mweight

Weight associated with the Reduction of Mobility Towards the Groundwater sub category.

Value: Reduce Toxicity Mweight

Weight associated with the Reduction in Toxicity category.

Value: Reduce Volume PT Mweight

Weight associated with the Volume of Principal Threat sub category.

Value: Reduce Volume TR Mweight

Weight associated with the Volume of Treatment Residual sub category,

Value: Reduce TMV Mweight

Weight associated with the Reduction of Toxicity, Mobility, or Volume sub criterion. This sub criterion is broken into two equally weighted categories: Reduction of Toxicity, Reduction of Mobility, and Reduction of Volume, The final two categories are further divided into two equally weighted sub categorize.

Value: Reduce Mobility Mweight

Weight associated with the Reduction of Mobility category.

Value: Reduce Volume Mweight

Weight associated with the Reduction of Volume category.

Value: Reliability and Availability Score

Score associated with the Reliability and Availability of Technology category under the Technical Feasibility sub criterion. The measure is the Percentage of Major Components Successfully Deployed in Similar Media,

For this measure Y = 2 in the train data nodes. Recall that data nodes are referred to as 'tX-Y' where, X refers to the train # and Y = the measure number.

Value: Ability to Construct Score

Scores associated with the Ability to Construct and Operate Category under the Technical Feasibility sub criterion. This category is measure by the Number of Major Systems Components in a Technology.

For this measure Y = 1 in the train data nodes, Recall that data nodes are referred to as 'tX-Y' where, X refers to the train # and Y = the measure number.

Value: Storage and Disposal Score

Scores Associated with the Availability of Storage and Disposal Services category under the Availability of Services and Materials sub criterion. The category is measured by the Percentage of Waste That Con Be Stored in Known Accepted Sites.

For this measure Y = 4 in the train data nodes. Recall that data nodes are referred to as 'tX_Y' where, X refers to the train # and Y = the measure number.

Value: Equipment and Services Score

Score associated with the Availability of Equipment and Services category under the Availability of Services and Materials sub criterion. The category is measured by the Number of Subcontractors or Contractors (whichever is the limiting factor) Willing to Place Bids.

For this measure Y = 3 in the train data nodes. Recall that data nodes are referred to as 'tX_Y' where, X refers to the train # and Y = the measure number.

Value: Administrative Feasibility Score

Scores associated with the Administrative Feasibility sub criterion under the Implementability criterion, The sub criterion is measured by the Percentage of Regulations (Relative to the Train 26) Which Apply,

For this measure Y = 5 in the train data nodes. Recall that data nodes are referred to as 'tX-Y' where, X refers to the train # and Y = the measure number.

Value: Reliability and Availability Value

Component value associated with the Reliability and Availability Value.

Value: Ability to Construct Value

Component values associated with the Ability to Construct Value

Value: Storage and Disposal Value

Component values associated with the Availability of Storage and Disposal Services Value.

Value: Equipment and Services Value

Component values associated with the Availability of Equipment and Services value.

Value: Administrative Feasibility Value

Component values associated with the Administrative Feasibility value.

Value: Work Protection Value

Component values associated with Worker Protection sub criterion under short-term effectiveness. The sub criterion is measured by a heuristic created by John Richardson and John Nonte at INEEL.

For this measure Y = 8 in the train data nodes. Recall that data nodes are referred to as 'tX_Y' where, X refers to the train # and Y = the measure number.

Value: Time Value

Component value associated with the Time Until Remedial Objectives Are Met sub criterion under Short-Term Effectiveness. The sub criterion is measured by the Number of Years Until Remedial Objectives are Met,

For this measure Y = 6 in the train data nodes. Recall that data nodes are referred to as 'tX_Y' where, X refers to the train # and Y = the measure number,

Value: Plant Impact Score

Score associated with Plant Impact category under the Environmental Impacts sub criterion. The category is measured by a qualitative scale based on the level of hazards to endangered plant species.

For this measure Y = 9 in the train data nodes, Recall that data nodes are referred to as 'tX_Y' where, X refers to the train # and Y = the measure number,

Value: Animal Impact Score

Scores associated with Animal Impact category under the Environmental Impacts sub criterion, The category is measured by a qualitative scale based on the level of hazards to endangered animals.

For this measure Y = 1 0 in the train data nodes. Recall that data nodes are referred to as 'tX_Y' where, X refers to the train # and Y = the measure number,

Value: Community Protection Score

Measure similar to the worker protection measure.

For this measure Y = 7 in the train data nodes. Recall that data nodes are referred to as 'tX_Y' where, X refers to the train # and Y = the measure number.

Value: Work Protection Value

Component values associated with the Worker Protection value.

Value: Time Value

Component values associated with the Time Until Remedial Objectives are Achieved value.

Value: Plant Impact Value

Component values associated with the Plant Impact Value, Note: for this measure the Value
is equal to the value.

Value: Animal Impact Value

Component values associated with Animal Impact value, Note: for this measure the Value is the some as the value.

Value: Community Protection Value

Component values associated with the Community Protection Score.

Value: Reduce Volume TR Score

Scores associated with the Volume of Treatment Residual sub category under the Reduction of Volume category, The sub category is measured by the Volume of the Treatment Residual/Volume of Media Containing Principal Threats Before Remediation.

For this measure Y = 17 in the train data nodes. Recall that data nodes are referred to as 'tX-Y' where, X refers to the train # and Y = the measure number.

Value: Resid Risk Score

Score associated with the Magnitude of Residual Risk sub criterion under long-term effectiveness. The sub criterion is measured by dividing the residual risk by the risk prior to remediation.

For this measure Y = 11 in the train data nodes. Recall that data nodes are referred to as 'tX_Y' where, X refers to the train # and Y = the measure number.

Value: Reliability of Managerial Controls Score

Score associated with the Reliability of Managerial Controls category under the Adequacy and Reliability of Controls sub criterion. The category is measured by the Probability of Exposure from Treated Residuals and Wastes On-Site to Human and Environmental Receptors Above Protective Levels.

For this measure Y = 13 in the train data nodes. Recall that data nodes are referred to as 'tX_Y' where, X refers to the train # and Y = the measure number,

Value: Management Required Score

Score associated with the Degree of Management Required category under the Adequacy and Reliability of Controls sub criterion. The category is measured by the Annual Long-Term Management Costs.

For this measure Y = 12 in the train data nodes. Recall that data nodes are referred to as 'tX_Y' where, X refers to the train # and Y = the measure number.

Value: Resid Risk Value

Component values associated with the Magnitude of Residual Risk sub criterion,

Value: Reliability of Managerial Controls Value

Component values associated with the Reliability of Managerial Controls category.

Value: Management Required Value

Component values associated with the Degree of Management Required category.

Value: Reduce Volume PT Score

Scores associated with the Reduction of Principal Threat Volume sub category under the Reduction of Volume category, The sub category is measured by the Percent Reduction of the Media Containing the Principal Threat,

For this measure Y = 16 in the train data nodes. Recall that data nodes are referred to as 'tX_Y' where, X refers to the train # and Y = the measure number,

Value: Reduce Toxicity Score

Scores associated with the Reduction of Toxicity category under the Reduction of Toxicity, Mobility, or Volume sub criterion under the Reduction of Toxicity, Mobility, or Volume Through Treatment Criterion. The category is measured by the Percent Reduction of the Principal Threat Mass,

For this measure Y = 20 in the train data nodes, Recall that data nodes are referred to as 'tX_Y' where, X refers to the train # and Y = the measure number.

Value: Reduce Mobility to GW Score

Scores associated with the Reduction of Mobility to the Groundwater sub category under the Reduction of Mobility category, The sub category is measured by the Percent Reduction of Access to the Groundwater Medium.

For this measure Y = 19 in the train data nodes, Recall that data nodes are referred to as 'tX_Y' where, X refers to the train # and Y = the measure number,

Value: Reduce Mobility to Air Score

Score associated with the Reduction of Mobility to Air sub category of the Reduction of Mobility category. The sub category is measured by the Percent Reduction of Mass Flow Rate of Contaminants Towards the Air.

For this measure Y = 18 in the train data nodes. Recall that data nodes are referred to as 'tX_Y' where, X refers to the train # and Y = the measure number.

Value: Irreversibility Score

Scores associated with the Irreversibility sub criterion under the Reduction of Toxicity, Mobility, or Volume criterion. The sub criterion is measured by the Percent of Principal Threats in an Irreversible Form.

For this measure Y = 15 in the train data nodes, Recall that data nodes are referred to as 'tX_Y' where, X refers to the train # and Y = the measure number,

Value: Amount PT Treated Score

Scores associated with the Amount of Principal Threats Treated sub criterion of the Reduction of Toxicity, Mobility, or Volume Through Treatment criterion. The sub criterion is measured by the Percent Mass of Principal Threats Treated.

For this measure Y = 14 in the train data nodes. Recall that data nodes are referred to as 'tX_Y' where, X refers to the train # and Y = the measure number.

Value: Reduce Volume TR Value

Component values associated with the Volume of Treatment Residual sub category.

Value: Reduce Volume PT Value

Component values associated with the Reduction of Principal Threat value.

Value: Reduce Toxicity Value

Component values associated with the Reduction of Toxicity value.

Value: Reduce Mobility to GW Value

Component values associated with the Reduction of Mobility to Groundwater value.

Value: Reduce Mobility to Air Value

Component values associated with the Reduction in Mobility to Air value,

Value: Irreversibility Value

Component values associated with the Irreversibility value.

Value: Amount PT Treated Value

Component values associated with the Amount of Principal Threats Treated value.

Value: Net Present Score

Scores associated with the Cost CERCLA criterion. The criterion is measured by the Net Present Value.

For this measure Y = 21 in the train data nodes. Recall that data nodes are referred to as 'tX_Y' where, X refers to the train # and Y = the measure number.

Value: Net Present Value

Component values associated with the Not Present Value,

Value: Cost Total Value

Cost is a CERCLA Criterion, The criterion is has only one measure, Net Present Value.

Appendix H: Technology Trains and Descriptions

The process options presented in Table 3.2 are briefly described below. Like in the strategy generation table, the process options are described according to their general response action.

No Action

Monitoring - Leaving the existing earthen cover in place and continuing the present level of monitoring activities and maintenance of surface water drainage at the SDA.

Institutional Controls

Legal Restrictions - Deeds and other legal documents that restrict entrance onto the site. Legal restrictions also prevent future use of the site for exploratory drilling.

Fencing - Erecting a ten foot tall steel security fence with three strands of barbed wire around the site. Access into the site is gained only through four steel gates.

Signs - Markers and diagrams warning intruders of the potential danger of entering the site. Markers are placed every 30 feet along boundary.

Cap

SDA - Alternating layers of varying thickness of rock, asphaltic concrete, sand, gravel, geotextile clay liners, basalt, and soil above the waste site.

Containment

Slurry/Grout Walls - Excavating trenches surrounding a contaminated site and filling with a slurry of grout materials such as clays or cement.

Sheet Piling - Driving vertical interlocking steel or concrete sheets around the waste.

Horizontal Drilling and Fractured Basalt Grouting - Drilling horizontal boreholes in the underlying basalt bedrock and grouting through the horizontal boreholes.

Conventional Mining - Using conventional underground mining techniques to excavate a barrier zone in the underlying bedrock and back-filling the excavation with cement grout.

In-Situ Treatment

Soil Vapor Extraction - Removes volatile and some semi-volatile contaminants from the soil by applying a vacuum to the soil. Gas leaving the soil is either treated and released to the air or destroyed.

In-Situ Vitrification - Uses an electric current to melt soil and waste at extremely high temperatures; immobilizing most inorganics and destroying organics. Inorganic pollutants are incorporated within the vitrified glass while water vapor and organic products are captured in a hood that removes particulates and other pollutants.

In-Situ Grouting - Drilling boreholes into the waste materials and applying grout through the boreholes that permeate into the waste, immobilizing or degrading the contaminants.

Retrieval

Gantry Mobile Building - Retrieval of waste by a crane surrounded by mobile building that contains all of the dust, contaminants, and organic pollutants.

In-Situ Modular Waste Retrieval - Large scale excavation, shredding, and treatment modules designed to operate within a waste trench or pit. Processed waste is discharged into the same pit or trench.

Remote Excavation - Retrieval of waste via hydraulic excavators controlled by operators in a control center away from the waste.

Ex-Situ Treatment/Stabilization

This analysis explores four different variations of ex-situ treatment/stabilization processes. The variations are explained below:

Baseline - Waste and intermixed soil are retrieved by a mobile gantry system. Soils and wastes are separated. Soils are chemically leached to remove transuranic contaminants. Recovered transuranics and shredded waste are vitrified in a Plasma Centrifugal Furnace. Clean soils are returned to the excavated pit. Vitrified glass is shipped to WIPP (Waste Isolation Pilot Plant).

Modified Baseline - Similar to Baseline. Does not use chemical leaching process. Shredded wastes and soils are passed through a Segmented Gate Processing System that separates low-level radioactive material from materials with elevated radioactivity. Low-level materials are returned to excavated pit, higher level materials are vitrified in a Plasma Centrifugal Furnace. Vitrified glass is shipped to WIPP.

Full Vitrification - Waste and intermixed soils are retrieved by a mobile gantry system and are processed through a Plasma Centrifugal Furnace. Low-level drummed glass is returned to excavated pit, higher level drummed glass is shipped to WIPP.

Incineration - Waste and intermixed soil are retrieved by a mobile gantry system and are processed through an incinerator. The incinerator volatilizes and combusts organics through very high temperatures. Inorganics are burned and turn to ash. Off-gases are treated and released to the air. Low-level ash is returned to pit, higher-level ash is drummed and shipped to WIPP.

Disposal

Engineered Vaults - Waste and intermixed soil is removed from the pits and placed into subsurface reinforced isolation silos constructed on-site.

WIPP (Waste Isolation Pilot Plant) - Placing waste (soil, ash, or glass) into drums and shipping to WIPP.

Appendix I: Train Evaluation Measure Scores

This appendix is broken into three sections. The first section provides the evaluation measure scores, provided by the INEEL technical experts, for each of the 27 trains (train 13 was removed from evaluation because it cannot apply to the SDA). The second section shows the score sheet given to the experts during the scoring sessions. Finally, the third section provides the comments given by the technical experts during the scoring sessions.

Table I.1 Evaluation measure scores for implementability measures.

SDA Alternatives		Implementability				
		Ability to Cnstrct	Reliability	Equip Avai	Disp Avail	Admin Feas
Train	Alternative					
1	No Action	1	100	5	100	0
2	Institutional Controls	2	100	5	100	0
3	Surface Barrier (cap)	3	100	5	100	10
4	Multiple Containment System	6	70	3	100	23
5		7	75	3	100	23
6		5	80	5	100	20
7		6	83	3	100	18
8		7	90	3	100	18
9		5	90	5	100	15
10		5	80	3	100	15
11		6	83	3	100	15
12	Surface Barrier and rem/tre VOC	4	100	5	100	10
13	In-situ tre/stab and Surface Barrier	5	60	1	100	50
14		4	75	4	100	20
15		6	50	1	100	50
16	Rem and onsite disp/stor	10	60	2	0	25
17		9	100	5	0	25
18		10	80	3	0	25
19	RPSIST and SB	11	55	1	100	75
20		10	50	2	0	75
21		10	90	1	100	75
22		9	89	4	0	75
23		11	73	1	100	75
24		10	70	3	0	75
25	RPSEST and SB	42	14	2	90	100
26		36	14	2	90	85
27		33	52	2	90	85
28		33	30	2	90	80

Table I.2 Evaluation measure scores for short-term effectiveness measures.

SDA Alternatives		Short-Term Effectiveness				
		Time	Com Prot.	Work Prot	Env Imp Plan	Env Imp Anin
Train	Alternative					
1	No Action	1000	10	10	0	0
2	Institutional Controls	1000	10	9.6	0	0
3	Surface Barrier (cap)	5	10	8.8	0	0
4	Multiple Containment System	10	6	7.6	0	0
5		25	6	7.2	0	0
6		10	6	8	0	0
7		11	6	7.6	0	0
8		25	6	7.2	0	0
9		10	6	8	0	0
10		11	6	8	0	0
11		25	6	7.6	0	0
12	Surface Barrier and rem/tre VOC	10	6	8.4	0	0
13	In-situ tre/stab and Surface Barrier	24	6	7	0	0
14		14	6	7.6	0	0
15		15	6	6.4	0	0
16	Rem and onsite disp/stor	24	4	2	0	0
17		15	4	2	0	0
18		8	4	2	0	0
19	RPSIST and SB	24	4	2	0	0
20		24	4	2	0	0
21		22	4	2	0	0
22		20	4	2	0	0
23		15	4	2	0	0
24		14	4	2	0	0
25	RPSEST and SB	25	0	0	0	0
26		25	0	0	0	0
27		25	0	0	0	0
28		25	0	0	0	0

Table I.3 Evaluation measure scores for long-term effectiveness measures.

SDA Alternatives		Long-Term Effectiveness		
		Resid Risk	Deg Mngmnt Rqrd (O&M/1000)	Rel Mngmnt Cont
Train	Alternative			
1	**No Action**	1	298	1
2	**Institutional Controls**	1	298	1
3	**Surface Barrier (cap)**	0.5	393	0.7
4	**Multiple Containment System**	0.38	428	0.3
5		0.38	428	0.3
6		0.45	428	0.4
7		0.38	393	0.3
8		0.38	393	0.3
9		0.45	393	0.4
10		0.38	393	0.3
11		0.38	393	0.3
12	**Surface Barrier and rem/tre VOC**	0.45	393	0.4
13	**In-situ tre/stab and Surface Barrier**	0.1	393	0.1
14		0.4	393	0.35
15		0.1	393	0.1
16	**Rem and onsite disp/stor**	0.3	393	0.4
17		0.3	393	0.4
18		0.3	393	0.4
19	**RPSIST and SB**	0.1	393	0.1
20		0.3	393	0.3
21		0.1	393	0.1
22		0.3	393	0.3
23		0.1	393	0.1
24		0.3	393	0.3
25	**RPSEST and SB**	0.1	393	0.1
26		0.1	393	0.1
27		0.1	393	0.1
28		0.1	393	0.1

Table I.4 Evaluation scores for reduction of toxicity, mobility, or volume through treatment measures.

SDA Alternatives		Reduction of Toxicity, Mobility, and Volume						
		Amnt PT Treat	Irrevers	Vol PT	Vol Resid	Mass Flow	Gw Access	Red Toxicity
Train	Alternative							
1	No Action	0	0	0	1	0	0	0
2	Institutional Controls	0	0	0	1	0	0	0
3	Surface Barrier (cap)	0	0	0	1	0	0	0
4	Multiple Containment System	17	17	30	0	75	17	50
5		17	17	30	0	75	17	50
6		17	17	30	0	75	17	50
7		17	17	30	0	75	17	50
8		17	17	30	0	75	17	50
9		17	17	30	0	75	17	50
10		17	17	30	0	75	17	50
11		17	17	30	0	75	17	50
12	Surface Barrier and rem/tre VOC	17	17	30	0	75	17	50
13	In-situ tre/stab and Surface Barrier	85	85	35	0.02	90	99	75
14		17	17	0	0.01	50	17	0
15		85	85	20	0.02	90	99	75
16	Rem and onsite disp/stor	0	0	0	1	0	0	0
17		0	0	0	1	0	0	0
18		0	0	0	1	0	0	0
19	RPSIST and SB	85	85	35	0.02	97	99	75
20		17	17	0	0.01	50	50	0
21		85	85	35	0.02	97	99	75
22		17	17	0	0.01	50	50	0
23		85	85	35	0.02	97	99	75
24		17	17	0	0.01	50	50	0
25	RPSEST and SB	85	85	90	0.25	98	100	100
26		85	85	75	0.02	98	100	100
27		85	85	60	0.02	98	100	100
28		85	85	0	0.02	98	100	100

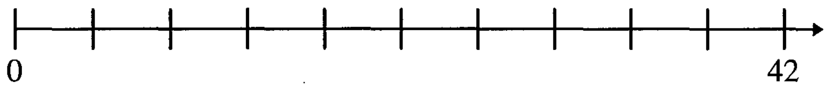
Table I.5 Evaluation measure scores for cost measure (provided by MSE).

SDA Alternatives		Cost
		NPV /1000
Train	Alternative	
1	No Action	11,037
2	Institutional Controls	11,499
3	Surface Barrier (cap)	110,562
4	Multiple Containment System	188,246
5		237,908
6		132,636
7		192,661
8		242,322
9		136,867
10		182,833
11		232,495
12	Surface Barrier and rem/tre VOC	127,040
13	In-situ tre/stab and Surface Barrier	216,198
14		176,548
15		290,428
16	Rem and onsite disp/stor	319,523
17		421,258
18		325,741
19	RPSIST and SB	320,163
20		227,182
21		318,649
22		317,680
23		202,056
24		190,161
25	RPSEST and SB	1,275,061
26		1,138,346
27		1,493,159
28		1,843,473

CERCLA Criteria Score Sheet

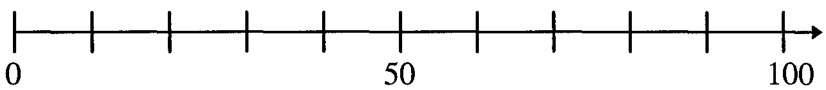
Implementability

- Ability to Construct and Operate the Alternative.



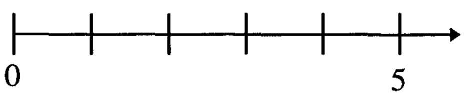
# of Major System Components

- Reliability of the Alternative.



% of Major System Components Successfully
Deployed in Similar Medium

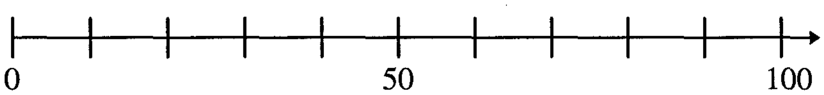
- Availability of Necessary Equipment and Specialists and Prospective Technologies



# of Contractors/Subcontractors Available

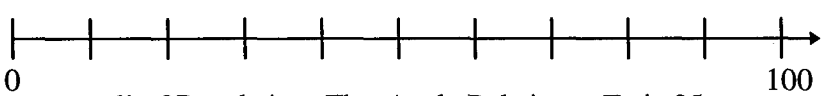
- Availability of Storage and Disposal Services

Assume WIPP is acceptable.



% of Waste That Can Be Stored and Disposed in Known and
Accepted Sites

- Administrative Feasibility



% of Regulations That Apply Relative to Train 25

Short-Term Effectiveness

- Time Until Remedial Response Objectives are Achieved.

0 1000

Years Until Remedial Objectives are Achieved

- Community Protection.

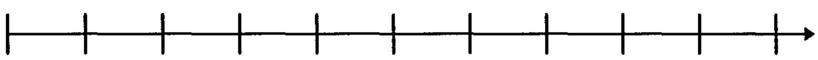
The score is based on a qualitative measure developed by John Richardson (from INEEL) that factors in the probability and associated consequences of a technology's threat to the community. See Appendix B for heuristic calculation.

- Worker Protection.

The score is a qualitative measure developed by John Richardson (from INEEL) that factors in the # of possible accidents that can affect workers. See Appendix B for heuristic calculation.

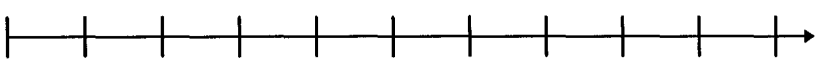
- Environmental Impacts.

- Plants



No Impact — Endangered Plant Impact

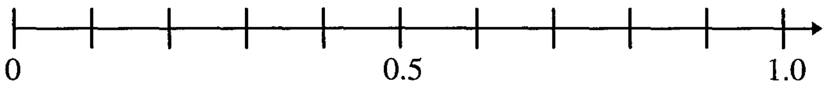
- Animals



No Impact — Endangered Animal Impact

Long-Term Effectiveness

- Magnitude of Residual Risk



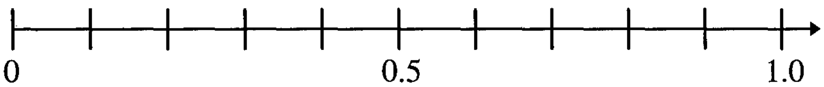
<u>Residual Risk</u>
Risk Prior to Remediation

- Adequacy and Reliability of Controls

- Degree of Management Required

Annual Long-Term Management Costs ($ Thousands) (Provided by MSE.)

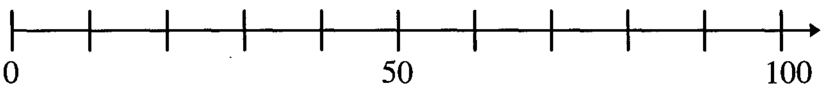
- Adequacy and Suitability Controls



Probability of Exposure From Treated Residuals and Waste On-Site
to Human and Environmental Receptors Above Protective Levels

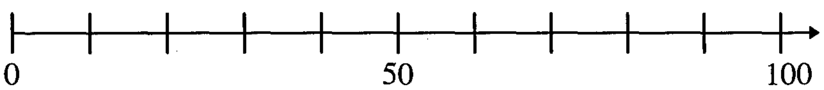
Reduction of Toxicity, Mobility, or Volume Through Treatment.

- Amount of Principal Threats Treated.



% Mass of Principal Threat *i* Treated

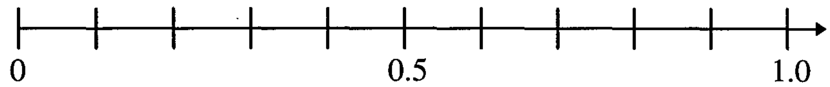
- Degree to which treatment is irreversible.



% of Principal Threats in an Irreversible Form

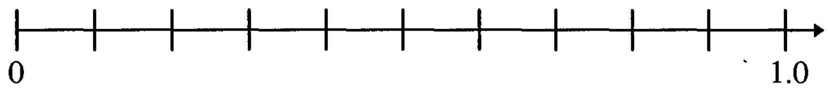
Volume Reduced.

- Reduction of Principal Threats Volume



$$\frac{\text{Volume Containing Principal Threats After Treat}}{\text{Volume Containing Principal Threats Before Treat}}$$

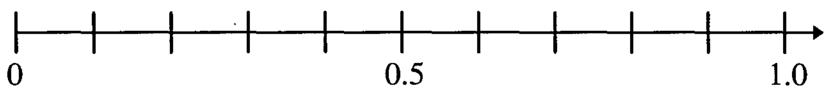
- **Volume of Treatment Residuals Produced**



$$\frac{\text{Volume of Treatment Residuals Produced}}{\text{Volume Containing Principal Threats Before Treat}}$$

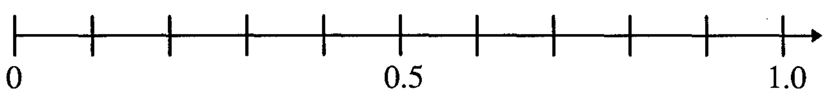
- **Mobility of Principal Threats Reduced.**

- Reduction of Mobility of Principal Threats to Air.



$$\frac{\text{Mass Flow Rate towards Air Pathway (after)}}{\text{Mass Flow Rate towards Air Pathway (before)}}$$

- **Reduction of Mobility of Principal Threat to Groundwater.**



$$\frac{\text{Access to Groundwater Pathway for Principal Threat } i \text{ After Treat}}{\text{Access to Groundwater Pathway for Principal Threat } i \text{ Before Treat}}$$

- **Reduction of Toxicity of Principal Threat (Non-radioactive principal threats)**

$$\frac{\text{Mass of Principal Threat } i \text{ After Treatment}}{\text{Mass of Principal Threat } i \text{ Before Treatment}}$$

Eliciting Train Scores From Technical Experts

The remainder of this appendix provides the comments provided by the experts while providing evaluation measure scores for the 27 trains analyzed in this report. Since this was a "first cut" at scoring the trains, the experts provided their best estimate for each alternative against each evaluation measure.

The expert groups (usually about 2 or 3 INEEL technicians) were given a description of the train and the scoring sheet shown previously. The scoring sheet shows the measures and their ranges, but not the component value functions. This eliminates the possibility of the experts applying a bias for or against an alternative since they don't know what scores provide high or low values.

In almost every measure, the experts discussed the score for one of the more commonly known trains within a category until they came to a consensus. After agreeing on the score for the most commonly known train, the experts scored the remaining trains in that group relative to the consensus score. For example, in the ex-situ treatment trains, the experts agreed that train 25 was the worst alternative in the "number of regulations that apply" measure. Thus, the remaining trains were given scores relative to train 25.

Technical Experts Comments During Scoring Sessions

Number of Major System Components

1 - Only monitoring. (1)

2 - Monitoring and institutional controls. (2)

3 - Monitoring, institutional controls, and the SDA cap. (3)

4 - Monitoring, institutional controls, SDA cap, soil vapor extraction with full thermal oxidation, slurry/grout walls, and horizontal drilling with grout. (6)

5 - Monitoring, institutional controls, SDA cap, soil vapor extraction with full thermal oxidation, slurry/grout walls, conventional mining, and clay or concrete fill. (7)

6 - Monitoring, institutional controls, SDA cap, soil vapor extraction with full thermal oxidation, and slurry/grout walls. (5)

7 - Monitoring, institutional controls, SDA cap, soil vapor extraction with full thermal oxidation, sheet piling, and horizontal drilling with grout. (6)

8 - Monitoring, institutional controls, SDA cap, soil vapor extraction with full thermal oxidation, sheet piling, conventional mining, and clay or concrete fill. (7)

9 - Monitoring, institutional controls, SDA cap, soil vapor extraction with full thermal oxidation, and sheet piling. (5)

10 - Monitoring, institutional controls, SDA cap, soil vapor extraction with full thermal oxidation, and horizontal drilling. (5)

11 - Monitoring, institutional controls, SDA cap, soil vapor extraction with full thermal oxidation, conventional mining, and clay or concrete fill. (6)

12 - Monitoring, institutional controls, SDA cap, and soil vapor extraction with full thermal oxidation. (4)

14 - Mining, institutional controls, off-gas treatment, cap with integrated grout. (4)

15 - Mining, institutional controls, off-gas treat, cap, grout, and ISV. (6)

16 - Building (2), crane, characterization, monitoring, controls, packaging, transport, engineered vault, and cap. (10)

17 - Remote mining machine, internal transport, characterization, monitoring, packaging, external transportation, vault, cap, control system. (9)

18 - Same as 16, except uses excavator rather than crane. (10)

19 - Monitoring, institutional controls, off-gas treatment, cap, and ISV + gantry technologies (6) = 11.

20 - Train 14 (4) + gantry technologies (6) = 10.

21 - Monitoring, institutional controls, off-gas treatment, cap, and ISV + mining technologies (5) = 10.

22 - Train 14 (4) + mining technologies (5) = 9.

23 - Monitoring, institutional controls, off-gas treatment, cap, and ISV + remote excavation technologies (6) = 11.

24 - Train 14 (4) + remote excavation technologies (6) = 10.

25 - Control, retrieval, assay, first transport, main robot, excavator, air monitor, gantry, HVAC, maintenance curtain, skids, shredder, second transport, box and drum, major separator, melter feed, primary chamber, torch, slag collector, melter control, secondary combustion chamber, quench, scrubbing, off-gas treatment, contain liquid waste, BEST system (3), preleach, leach, precipitation, acid recovery, sulfate conversion, control, maintenance melter, utilities, chemical storage, packaging, transport to pit, residual transport, institutional controls, and cap. (42)

26 - First 25 technologies of train 25 + belt, transfer, and sensors + the last 8 technologies of train 25. (36)

27 - The first 25 technologies of train 25 and the last eight technologies of train 25. (33)

28 - The first 25 technologies of train 25, except plasma melter is replaced with an incinerator and residual transport is changed to shipment to WIPP. Finally, add the last 8 technologies of train 25. (33)

Percent of Major System Components Successfully Deployed in Similar Media

1 - Done everywhere. (100)

2 - Currently applied at the site. (100)

3 - Many other sites have used caps. (100)

4 - 12 - monitoring, institutional controls, cap, and soil vapor extraction have been successfully deployed in other sites. However, the sheet pilings, grout walls, drilling, and mining combinations have only been partially deployed. The technicians gave their best estimates on the relative percent of the technologies that have been deployed at other sites.

14 - Grouting has never been performed on "hot spots" before. (75)

15 - Contains grouting and ISV, neither has been successfully deployed in similar media. (50)

16 - All but the mobile building (2) and the crane and its controls have been applied elsewhere. (60)

17 - All components have been used before. (100)

18 - All but the mobile building (2 major systems) have been used before. (80)

19 - ISV, mobile building (2), and the crane and its controls have not been deployed. (55)

20 - Grouting, mobile building (2), and the crane and its controls have not been deployed. (50)

21 - Only ISV has not been deployed. (90)

22 - Only grouting has not been deployed. (89)

23 - ISV and mobile building (2) have not been deployed. (73)

24 - Grouting and mobile building (2) have not been deployed. (70)

25 - 6 of the 42 technologies have been successfully deployed. (14)

26 - 5 of the 36 technologies have been successfully deployed. (14)

27 - Vitrifying everything eliminates separation steps that have never been deployed. (52)

28 - Incinerators have been deployed before. (30)

Number of Subcontractors/Contractors Available

1 - fully available, does not need to be subcontracted out. (5)

2 - See train 1. (5)

3 - Many groups can and have built caps at other sites. (5)

4 - Only three bidders for horizontal drilling. (3)

5 - Only three bidders for conventional mining. (3)

6 - No problem getting five or more bidders for each process. (5)

7 - See train 4. (3)

8 - See train 5. (3)

9 - See train 6. (5)

10 - See train 4. (3)

11 - See train 5. (3)

12 - See train 6. (5)

14 - Should not have trouble getting four bids. (4)

15 - ISV joule heater is owned by GEOSAFE. (1).

16 - Only 2 bids for gantry mobile building. (2)

17 - No problem getting bids. (5)

18 - Only 3 bids for remote excavators. (3)

19 - See Train 15. (1)

20 - See Train 16. (2)

21 - See Train 15. (1)

22 - See Train 14 (4)

23 - See Train 15. (1)

24 - See Train 18. (3)

25 - 28 - 2 contractors placed bids on the pilot study using Train 25. Assume the same for the other variations. (2)

Percent of Waste That Can Be Stored and Disposed in Known and Accepted Sites

1, 2, 3 - The waste stays on site so there is no storage problems. (100)

4 - 12 - Waste is treated in situ. It never leaves the pit and stays on site. (100)

14 - Grouting is done in situ so the waste stays on site. (100)

15 - Treats the waste through in-situ methods. Thus, the waste stays on site. (100)

16, 17, 18 - Vaults will require additional storage space. (0)

19, 21, 23 - See Train 15. (100)

20, 22, 24 - Grouting after excavating the waste will require even more volume on the to dispose the grouted waste. (0)

25 - 28 - Should be able to either place waste back into pit or send to WIPP. Might have difficulty finding disposal sites for vitrified (or ash) end product that is too radioactive to place back into pits, but not radioactive enough to send to WIPP. (90)

Number of Regulations That Apply

1 - No additional regulations than what currently applies. (0)

2 - See train 1. (0)

3 - Requires more regulations than the previous trains. (10)

4 - About 10% from soil vapor extraction and 10% for slurry/grout walls and 5% for drilling under the site. It is assumed that 2% of the regulations overlap between the slurry/grout walls, and drilling (-2%). (23)

5 - About 10% from soil vapor extraction and 10% for slurry/grout walls and 5% for mining under the site. It is assumed that 2% of the regulations overlap between the slurry/grout walls, and mining (-2%). (23)

6 - About 10% from soil vapor extraction and 10% for slurry/grout walls. (20)

7 - About 10% from soil vapor extraction, 5% for sheet piling, and another 5% for drilling underneath the site. It is assumed that 2% of the regulations overlap between sheet piling and the drilling (- 2%). (18)

8 - About 10% from soil vapor extraction, 5% for sheet piling, and another 5% for mining underneath the site. It is assumed that 2% of the regulations overlap between sheet piling and the mining (- 2%). (18)

9 - About 10% from soil vapor extraction and 5% for sheet piling. (15)

10 - About 10% from soil vapor extraction and another 5% for drilling under the waste site. (15)

11 - About 10% from soil vapor extraction and another 5% for mining under the waste site. (15)

12 - About 10% of the regulations as a result of using soil vapor extraction with thermal oxidation. (10)

14 - Holes must be drilled into the waste. This will require some regulations. (20)

15 - ISV will require several regulations, but not as much because WIPP requirement do not need to be met. (50)

16, 17, 18 - Disturbing the waste requires some regulations. (25)

19 - 24 - The excavating and in-situ methods will require many regulations, but not as many as the pilot train 25 process. (75)

25 - This train is the baseline. (100)

26, 27 - Not having the chemical treatment reduces the applicable regulations. (85)

28 - Incinerator requires even fewer regulations. (80)

Years to Remediate the Site

1 - Takes thousands of years for the contaminants to naturally attenuate. (1000)

2 - See train 1. (1000)

3 - Cap meets groundwater remedial objective. Cap is built in five years. (5)

4 - 28 - Analysis performed by MSE. See Appendix J.

Community Protection Waste? (see heuristic in Appendix B)

1 - 2 ==> 10 - 1000 * 0 = 10

3 ==> 10 - 5 * 0 = 10

4 - 15 ==> 10 - 1 * 4 = 6

16 - 24 ==> 10 - 1 * 6 = 4

25 - 28 ==> 10 - 1 * 10 = 0

Worker Protection (see heuristic in Appendix B)

1 ==> 10 - 0.1 *1 * 0 = 10.

2 ==> 10 - 0.1 * 2 * 2 = 9.6.

3 ==> 10 - 0.1 * 3 * 4 = 8.8.

4 ==> 10 - 0.1 * 6 * 4[1] = 7.6.

5 ==> 10 - 0.1 * 7 * 4 = 7.2.

6 ==> 10 - 0.1 * 5 * 4 = 8.

7 ==> 10 - 0.1 * 6 * 4 = 7.6.

8 ==> 10 - 0.1 * 7 * 4 = 7.2.

9 ==> 10 - 0.1 * 5 * 4 = 8.

10 => 10 - 0.1 * 5 * 4 = 8.

11 => 10 - 0.1 * 6 * 4 = 7.6.

12 => 10 - 0.1 * 4 * 4 = 8.4.

14 => 10 - .1 * 4 * 6 = 7.6.

15 => 10 - .1 * 6 * 6 = 6.4.

16 - 24 => 10 - 1.0 * 8 = 2.

25 - 28 => 10 - 1 * 10 = 0.

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[1] While soil vapor extraction is an in-situ treatment, it does not penetrate the waste. Thus, trains 4 - 12 receive a consequence score of 4 (rather than 6 for in-situ treatment) because containing the waste is their main feature.

Plant Impacts

None of the trains impact plants.

Animal Impacts

None of the trains impact animals.

Residual Risk Divided by Risk Prior to Remediation

1 - Nothing is done to the site. (1)

2 - Nothing is done to the waste on the site. (1)

3 - Nothing is done to the waste, but the cap does decrease the risk by reducing water filtration rate, and erosion. (0.5)

4 - Cap reduces risk to 0.5, soil vapor extraction reduces risk an additional 0.05, and the drilling (with grout fill) further reduces risk an additional 0.07. (0.38)

5 - Cap reduces risk to 0.5, soil vapor extraction reduces risk an additional 0.05, and the mining (with clay or concrete fill) further reduces risk an additional 0.07. (0.38)

6 - Cap reduces risk to 0.5 and soil vapor extraction reduces risk and additional 0.05. (0.45).

7 - Cap reduces risk to 0.5, soil vapor extraction reduces risk an additional 0.05, and drilling (with grout fill) further reduces risk an additional 0.07. (0.38)

8 - Cap reduces risk to 0.5, soil vapor extraction reduces risk an additional 0.05, and mining (with clay or concrete fill) further reduces risk an additional 0.07. (0.38)

9 - See train 6. (0.45)

10 - See train 4 .(0.38)

11 - See train 5. (0.38)

12 - See train 6. (0.45)

14 - Grouting does not remove the VOC's very well. (0.4)

15 - ISV technology is good at handling VOC's and hot spots. (0.1)

16, 17, 18 - Placing waste into vaults greatly reduces risk of exposure. However, the vaults may fail over thousands of years. (0.3)

19, 21, 23 - See train 15. (0.1)

20, 22, 24 - See train 14. However since the waste is first removed from the pit and sorted, ISV performs better. Thus, a lower probability. (0.3)

25 - 28 - All variations do a very good job of eliminating most of the risk. (0.1)

Annual Long-Term Management Cost ($Millions)

Analysis Performed by MSE. See Appendix J.

Probability of System Failure

1 - Doing nothing does not achieve remedial action objectives. (1)

2 - See train 1. (1)

3 - The cap does provide suitable protection for the next few hundred years, but there is no guarantee it will be effective thousands of years into the future. (0.7)

4 - 12 - The cap reduces the probability to 0.17. Soil vapor extraction further reduces the risk and additional 0.3. Finally, drilling and filling basalt cracks or mining and filling with concrete reduce the risk another 0.1. Thus trains 4, 5, 7, 8, 10, and 11 have a score of 0.3 and trains 6, 9, and 12 have a score of 0.4.

14 - Grout can crack and can't be shown to last thousands of years (0.35)

15 - Glass produced through ISV is reliable on both hot spots and VOCs. Thus, adding ISV reduces the risks associated with the grout cracks. (0.1)

16, 17, 18 - Chance of vault failure (0.4)

19, 21, 23 - Glass produced through ISV is reliable on both hot spots and VOCs. (0.1)

20, 22, 24 - See Train 14. However, since the waste is first removed and sorted the ISV process works better. Thus the probability of failure is less than train 14. (0.3)

25 - 28 - Like ISV, the vitrified waste from ex-situ vitrification lasts a very long time and has little chance of failure. (0.1)

Note: Trains 1, 2, 3 and 16, 17, 18 do not treat the waste. They will receive utilities of 0 for the Reduction of Toxicity, Mobility, or Volume Through Treatment CERCLA Criterion.

Percent Mass of Principal Threats Treated

4 - 12 - Soil vapor extraction will remove/destroy 17% of the VOCs. (17)

14 - Reduces mobility by containing waste, but does not treat organics. (17)

15 - Vitrifies the inorganics and burns off organics in addition to stopping mobility. (85)

19, 21, 23 - Vitrifies the inorganics and burns off organics. (85)

20, 22, 24 - See Train 14. (17)

25 - 28 - Does a good job of treating all of the principal threats, except carbon-14. (85)

Percent of Principal Threats in an Irreversible Form

The technical experts assumed that all treatment processes were irreversible. Thus the scores for this measure are exactly the same as the previous measure

Percent Reduction of Principal Threats

4 - 12 - Soil vapor extraction does a good job at reducing VOC volume. (30)

14 - Grouting does not reduce volume, it fills in voids. (0)

15 - Vitrification will reduce volume, while grouting will increase volume. (20)

19, 21, 23 - Vitrification has been shown to reduce volume by 35%. (35)

20, 22, 24 - See train 14. (0)

25 - This variation reduces the volume the most because the pretreatment steps concentrate the principal threats. (90)

26 - Segmented gate process concentrates the principal threats, but not as much as train 25. (75)

27 - Full vitrification does not concentrate the principal threats at all. The volume reduction is a result of the vitrification process only. (60)

28 - Incineration greatly reduces the volume of the principal threats. However, additives must be added to stabilize the ash. This negates the volume reduction. (0)

Volume of Treatment Residual Produced Divided by Volume of Media Containing Principal Threat

4 - 12 - No residual waste is created in the trains that do not drill or mine. In the trains, the residual waste is minimal. (0)

14 - Practically no residual waste. (0.01)

15 - Practically no residual waste. However, slightly more than train 14 if the probes are left in the pit. (0.02)

19, 21, 23 - Practically no residual waste (0.02)

20, 22, 24 - See Train 14 (0.01)

25 - Chemical process produces a large amount of residual wastes (one of the main reasons it was discontinued). (0.25)

26 - 28 - minimal residual waste. (0.02)

Percent Reduction of Mass Flow Rate

4 - 12 - Since most of the VOCs are removed, the mobility towards the air is greatly reduced. (75)

14 - Does not treat organics. However, even if organics are not treated, their mobility is significantly reduced due to the grout (but not as much as when vitrified). (50)

15 - Vitrifies the inorganics and burns off organics. Even if a principal threat is not treated, its mobility is significantly reduced because of the glass. (90)

19, 21, 23 - Vitrifies the inorganics and burns off organics. Even if a principal threat is not treated, its mobility is significantly reduced because of the glass. However, excavating and separating the waste prior to ISV improves the process; resulting in a higher percentage than ISV alone. (97)

20, 22, 24 - See train 14. (50)

25 - 28 - Like ISV, these variations leave the waste in a form that makes it difficult for contaminants to move towards the surface. Since the vitrification is ex-situ, the glass is in a slightly better condition. (98)

Percent Reduction in Groundwater Access

4 - 12 - Soil vapor extraction only slightly reduces access to groundwater (17)

14 - Grouting may break and leave pathways to groundwater, Grouting process may actually increase contaminant tendency towards groundwater. (17)

15 - Very difficult for contaminants to travel towards groundwater. (99)

19, 21, 23 - See train 15. (99)

20, 22, 24 - See train 14. However, excavating the waste prior to removal allows better grouting; resulting in a higher percentage than in-situ grouting. (50)

25 - 28 - These variations completely eliminate contaminant access to groundwater. (100)

Percent Reduction of Principal Threats Masses

4 - 12 - Soil vapor extraction destroys 50 percent of the non-radioactive COCs. (50)

14 - Does nothing to remove mass of principal threats. (0)

15 - Removes most VOCs from site. (75).

19, 21, 23 - See train 15. (75)

20, 22, 24 - See train 14. (0)

25 - 28 - Since all of the non-radioactive principal threats are organics, they are all destroyed in the vitrification process. (100)

Net Present Value

Analysis Performed by MSE. See Appendix J.

Appendix J: Technology Train Cost Model Assumptions and Calculations

Overview

The following material provides MSE's documentation (written by Steve Antonioli and Douglas Abbot) concerning the methodology and/or assumptions used to derive costs for each treatment train. A description of each treatment train component and its associated cost is included as well as any reference material that was used for supporting documentation. Each "bullet" indicates a component technology which has not yet been discussed. Any accompanying calculations performed for each technology are included. Finally, all estimates used are rounded to the nearest thousand dollar.

Treatment train #1: Monitoring (no action)

The **WAG-7 TRU Pits and Trenches RD/RA Preliminary Baseline Summary Report** (Baseline report) estimated an annual summary total cost of $393,000 for "Long Term Monitoring (WBS-143).

Calculations: none

The following annual costs were deleted from the $393,000 annual cost total due to the assumption that a cap is not included in this treatment train: cost of SDA grounds ($45,000), cap perimeter flood control cost ($20,000), and irrigation cost ($30,000). These exclusions yielded a total annual cost of $298,000.

Calculations:	$393,000
	($45,000)
	($20,000)
	($30,000)
	$298,000

A net present value (NPV) of $11,037,037 was determined based on an the total annual cost of $298,000 and a discount rate of 2.7%. The NPV amount indicates the amount of money which must be "set aside" to cover the yearly interest cost of this treatment train, which would continue into the future indefinitely.

Calculations: $298,000/0.027 = $11,037,037

Treatment train #2: Treatment train #1 plus fencing, signs, and legal restrictions

A facilities map contained in **A BRIEF ANALYSIS AND DESCRIPTION OF TRANSURANIC WASTES IN THE SUBSURFACE DISPOSAL AREA OF THE RADIOACTIVE WASTE MANAGEMENT COMPLEX AT INEEL** was used to estimate the perimeter of the SDA. A perimeter of 10,000 lineal feet (lf) was assumed for calculation purposes.

Calculations: none

Fencing/Gate

The **Environmental Cost Handling Options and Solutions (ECHOS) Environmental Restoration Assemblies Cost Book** provided a fencing cost estimate of $49.91 per lf. This represents the highest safety level cost for a fence with the following characteristics: security fence, w/1'x1' grade beam, 10' galvanized w/3 strands barbed wire. Also, four gates, at a cost of $612 per gate (highest safety level), were assumed. Total estimated fencing and gate costs are $499,000 and $2,448, respectively

Calculations: 10,000 lf x $49.91/lf = $499,000
4 x $612 = $2,448

Signing

The **ECHOS Cost Book** provided a hazardous waste signing cost estimate of $81.49 per sign. This represents the highest safety level cost. The number of signs needed to adequately identify the area was 334, which was based on an assumption of one sign posted every 30 feet. The resultant signing cost is $27,218.

Calculations: 10,000 ft ÷ 30 ft/sign = 334 signs
334 x $81.49 = $27,218

Legal Restrictions

The law firm of Corrette, Pohlman & Keebe, located in Butte Montana, provided an estimate of $5,000 for legal fees pertaining to the legal restrictions component of this treatment train. It was assumed that a legal document similar to a conservation easement would need to be created for a hazardous waste site, approximately 100 acres in size.

Calculations: none

Treatment train #3: Treatment train #2 plus SDA cap

SDA Cap[1]

The **Baseline Report** estimated a total cost of $105,473,000[2] for the SDA Cap (WBS 141).

1. The cost of fencing and signs from treatment train #2 was not included in the cost estimate for treatment train #3. Fencing and signs is included in the SDA Cap estimate.

2. See **Baseline Report** for annual capital and O&M costs.

Treatment train #4: Treatment train #3 plus soil vapor extraction (SVE) plus slurry wall plus horizontal drilling with fractured basalt grouting

Soil Vapor Extraction (SVE)
Battelle Memorial Institute's RE-OPT Database (Montana Tech Library) indicated that extraction wells should be emplaced throughout a site at distances of 15-100 feet. The SDA site was assumed to contain unconsolidated matter (similar to a landfill) with correspondingly high porosity and permeability. Due to the assumptions of porosity and permeability, 100 foot spacing for the extraction wells was used. The total number of wells required to service the 96.8 acre (4,216,608 ft^2) SDA site is 537 wells.

<u>Calculations:</u>

1 acre = 43,568 ft^2
96.8 acres x 43,568 ft^2/acre = 4,216,608 ft^2

100' spacing
radius (r) = 50'
Area of influence (per well) = r^2
= $(50)^2$ = 7,850 ft^2
4,216,608 ft^2 $\div$ 7,850 ft^2/well = 537 wells

Cost data contained in the Los Alamos report, **A COMPENDIUM OF COST DATA FOR ENVIRONMENTAL RESTORATION TECHNOLOGIES, METHODS, AND PROCESSES** (Compendium), were used to estimate the capital and operating/maintenance costs for SVE. The compendium contained cost data for SVE wells drilled in lithology similar to the SDA's lithology (mixed sandy, silty, clayey) and the well depth and well screen lengths in the compendium (30 feet and 25 feet, respectively) were similar to the wells required at INEEL. Total capital costs for the SVE technology were $11,070,255 and total annual operating costs were $1,745,250.

<u>Calculations:</u>

site area[1] = 40,000 ft^2
well spacing[1] = 35 ft
radius (r)[1] = 17.5 ft use 18 ft
area of influence (per well) = r^2
= $(18)^2$ = 1,017 ft^2
40,000 ft^2 $\div$ 1,017 ft^2 = 40 wells
total capital cost[1] = $620,000
capital cost per well = $15,500

537 wells (INEEL)x \$15,500/well = \$8,323,500
\$8,323,500 x 1.33^2 = \$11,070,255
annual operating cost[1] = \$130,000
operating cost = \$3,250/yr/well
537 wells (INEEL) x \$3,250 = \$1,745,250

1. Cost compendium data.

2. The 1.33 cost adjustment factor is used to incorporate design and management costs at INEEL. This adjustment factor is identical to factors used by ETCAP at the Los Alamos National Laboratory.

Slurry Wall

The **Cost Compendium** contained engineering estimates ranging from \$4.50-\$13.86 per square foot and actual expenditures ranging from \$0.25 per square foot to \$31.96 per square foot. The **ASSESSMENT OF BARRIER CONTAINMENT TECHNOLOGIES: A Comprehensive Treatment for Environmental Remediation Applications** provided an estimate of \$15 per square foot and this estimate was used in the calculations since it fell into the mid-range of the actual expenditures and into the high range of the engineering estimates. A total capital cost of \$4,987,500 is estimated for a slurry wall 10,000 feet long (assumed perimeter of SDA) by 25 feet deep.

Calculations:

area of slurry wall = 10,000 ft x 25 ft = 250,000 ft^2
\$15/ft^2 x 250,000 ft^2 = \$3,750,000
\$3,750,000 x 1.33 = \$4,987,500

Scaled-up estimates from the **Cost Compendium** yield a an annual maintenance cost of \$3.50/linear foot or \$35,000 per year. This cost is necessary for surface maintenance and is assumed to be a perpetual cost.

Horizontal Drilling with Fractured Basalt Grouting

The **MSE Cost Book** contained horizontal well drilling cost estimates in the range of \$25-\$75 per linear foot. The high-end figure was used for drilling cost estimates. An assumed 10.5 foot radius zone of influence was obtained from **Pressure Grouting of Fractured Basalt Flows** and 20 foot hole spacing was assumed. The holes would be drilled perpendicular to the SDA's southern boundary which would yield 222,000 linear feet of required drilling. 185 holes would be required with an average length of 1200 feet (determined graphically). A hole drilled within these parameters would cost \$90,000. The total drilling cost would be \$16,650,000.

Calculations:

1200 ft x \$75/ft = \$90,000/hole
\$90,000/hole x 185 holes = \$16,650,000

The **Pressure Grouting of Basalt Flows** document provided a grout cost estimate of $159.75 per linear foot. The total cost to grout 222,000 linear feet is $35,464,500.

Calculation: 222,000 linear ft x $159.75/linear ft
= $35,464,500

The total cost to horizontally drill and grout the aforementioned holes is estimated to be $69,312,285.

Calculation: $16,650,000 + $35,464,000 = $52,114,500
$52,114,500 x 1.33 = $69,312,285

For this treatment train, it is assumed that the SDA cap would be installed first (year one). The cap would take 4 years to complete (**Baseline Report** estimate). All further operations (monitoring, SVE, slurry wall, & horizontal drilling/grouting) would commence in the fifth year.

It was assumed that a crew could drill and grout 100 ft per day. This resulted in an estimated project completion time of 6.34 years. For calculation purposes, it was assumed that the fractional component (.34 year) occurred in the fifth year of the treatment train and the remainder of the project (6 years) occurred in years six through eleven.

Treatment train #5: Treatment train #3 plus SVE plus slurry wall plus conventional mining

This treatment train is identical to train #4 except that the horizontal drilling with fractured basalt grouting component is replaced with conventional mining.

Conventional Mining
The total capital cost to conventionally mine the 96.8 acre SDA site is estimated to be $2,275,000. This estimate is based upon cost data gathered from **Western Mine Engineering's Mining Cost Summaries**. This capital cost figure is based upon three access ramps and haulage drifts (12 ft wide,10 ft high).

Calculations: $1,711,000 x 1.33 = $2,275,000

Production costs are estimated to be $101,647,000 for excavation and $43,619,000 for concrete backfill. The assumed crosscut for mining operations is 8 feet wide and 7 feet deep. **Western Mine Engineering's Mining Cost Summaries** provided a mining cost estimate of $145 per linear foot and $30/yd concrete from an on-site concrete batch plant. It is assumed that, at a mining rate of 22,000 ft/yr, it will take 24 years to complete the mining project at an annual cost of $6,053,000.

Calculations: 96.8 acres x 43,568 ft^2/acre = 4,216,625 ft^2
4,216,625 ÷ 8 ft trench width = 527,078 lf
527,078 lf x $145/lf = $76,426,310
$76,426,310 x 1.33 = $101,647,000
4,216,625 lf x 7 ft depth = 29,516,375 ft^3
29,516,375 ft^3 ÷ 27 ft^3/yd^3 = 1,093,000 yd^3
1,093,000 yd^3 x $30/$yd^3$ = $32,795,972
$32,795,972 x 1.33 = $43,619,000
527,076 lf ÷ 22,000 ft/yr = 24 years
($101,647,000 + $43,619,000) ÷ 24 years
= $6,053,000 annual cost

Treatment train #6: monitoring plus SDA cap plus SVE plus slurry wall

Monitoring[1]: annual cost = $298,000
net present value = $11,037,037

SDA CAP[2]: total cost = $105,473,000

SVE[3]: total capital cost = $11,070,255
annual operating cost = $1,745,250

Slurry wall[4]: total capital cost = $4,987,500
annual maintenance cost = $35,000

1. See treatment train #1 for detail.
2. See treatment train #3 for detail.
3. See treatment train #4 for detail.
4. See treatment train #4 for detail.

Treatment train #7: monitoring plus SDA Cap plus SVE plus horizontal drilling with fractured basalt grouting plus sheet piling

Sheet Piling

As previously mentioned in treatment train #4, it is assumed that the SDA Cap will be installed in years 1 through 4 and then all other activities can proceed beginning in year 5. The total sheet piling cost, which is assumed to occur entirely in year 5, is estimated to be $11,228,000.

Calculations: 10,000 lf trench x 25 ft deep = 250,000 ft^2
$21.74/$ft^2$ installed cost (**Cost compendium** - 1980 cost)

construction equipment & labor escalator = 1.55
(Consumer Price Index 1980-96)
$\$21.74/ft^2 \times 1.55 = \$33.76/ft^2$ (1996 $'s)
$\$33.76/ft^2 \times 1.33 = \$44.91/ft^2$ (adjusted)
$\$44.91/ft^2 \times 250{,}000\ ft^2 = \$11{,}228{,}000$

Monitoring[1]: annual cost = $298,000
net present value = $11,037,037

SDA Cap[2]: total cost = $105,473,000

SVE[3]: total capital cost = $11,070,255
annual operating cost = $1,745,250

Horizontal drilling/grouting[4]: total cost = $69,312,285

1. See treatment train #1 for detail.
2. See treatment train #3 for detail.
3. See treatment train #4 for detail.
4. See treatment train #4 for detail.

Treatment train #8: monitoring plus SDA cap plus SVE plus sheet piling plus conventional mining

Monitoring[1]: annual cost = $298,000
net present value = $11,037,037

SDA Cap[2]: total cost = $105,473,000

SVE[3]: total capital cost = $11,070,255
annual operating cost = $1,745,250

Sheet piling[4]: total capital cost = $11,228,000

Conventional mining[5]: total capital cost = $2,132,000 annual production cost = $6,053,000

1. See treatment train #1 for detail.
2. See treatment train #3 for detail.
3. See treatment train #4 for detail.
4. See treatment train #7 for detail.
5. See treatment train #5 for detail.

Treatment train #9: monitoring plus SDA Cap plus SVE plus sheet piling

Monitoring[1]: annual cost = $298,000
net present value = $11,037,037

SDA Cap[2]: total cost = $105,473,000

SVE[3]: total capital cost = $11,070,255
Sheet piling[4]: total capital cost = $11,228,000

1. See treatment train #1 for detail.
2. See treatment train #3 for detail.
3. See treatment train #4 for detail.
4. See treatment train #7 for detail.

Treatment train #10: monitoring plus SDA Cap plus SVE plus horizontal drilling with fractured basalt grouting

Monitoring[1]: annual cost = $298,000
net present value = $11,037,037

SDA Cap[2]: total cost = $105,473,000
SVE[3]: total capital cost = $11,070,255
annual operating cost = $1,745,250

Horizontal drilling/grouting[4]: total cost = $69,312,285

1. See treatment train #1 for detail.
2. See treatment train #3 for detail.
3. See treatment train #4 for detail.
4. See treatment train #4 for detail.

Treatment train #11: monitoring plus SDA Cap plus SVE plus conventional mining

Monitoring[1]: annual cost = $298,000
net present value = $11,037,037

SDA Cap[2]: total cost = $105,473,000
SVE[3]: total capital cost = $11,070,255
Conventional mining[4]: total capital cost = $2,132,000
annual production cost = $6,053,000

1. See treatment train #1 for detail.
2. See treatment train #3 for detail.
3. See treatment train #4 for detail.
4. See treatment train #5 for detail.

Treatment train #12: monitoring plus SDA Cap plus SVE

Monitoring[1]: annual cost = $298,000
net present value = $11,037,037
SDA Cap[2]: total cost = $105,473,000

SVE[3]: total capital cost = $11,070,255

1. See treatment train #1 for detail.
2. See treatment train #3 for detail.
3. See treatment train #4 for detail.

Treatment train #14: monitoring plus SDA Cap plus in situ grouting

In Situ Grouting
The **Innovative Grouting/Retrieval Demonstration Final Report** (IG Report) indicated that 24,000 grout holes are required per acre to successfully create a stable monolith. The **IG Report** also provided a drilling/grouting time of 40 minutes per hole.

The **PD Study** stated the area of concern is 14 acres. This includes pits 1 through 6, pit 10, and trenches 1 through 10. 336,000 grouting holes would be required to stabilize the 14 acres with an associated drilling/grouting time of 224,000 hours.

Calculations:
14 acres x 24,000 holes/acre = 336,000 holes
336,000 holes x 40 min/hole = 13,440,000 min.
13,440,000 ÷ 60 min/hr = 224,000 hours

It was assumed that, because of the large number of required drilling/grouting hours, 10 grouting rigs would be used for the job. Each rig would be required to run for a total of 22,400 hours over the 10 year life of the project. Assuming 250 days per year, each rig would run for 9 hours per day.

Calculations:
224,000 total hours ÷ 10 rigs = 22,400 hrs/rig
224,000 hrs/rig ÷ 10 yr project life = 2,240 hrs/rig/yr
2,240 hrs/rig/yr ÷ 250 days/yr = 9 hr/day

The **IG Report** provided cost per hole data which yielded a total annual cost of $11,760,000.

Calculations:
$250 drilling expense/hole
$100 material expense/hole
$350 per hole

$350/hole x 336,000 holes = $117,600,000 total cost
$117,600,000÷10 yr proj life= $11,760,000 ann.O&M cost

Finally, it is assumed that the grouting component would be undertaken initially and the SDA cap component would commence in year 11.

Monitoring[1]: annual cost = $298,000
net present value = $11,037,037

SDA Cap[2]: total cost = $105,473,000

1. See treatment train #1 for detail.
2. See treatment train #3 for detail.

Treatment train #15: monitoring plus SDA Cap plus in situ grouting plus in situ vitrification

This treatment train is based upon the assumption that once in situ grouting has occurred and a stable monolith has been created, then ISV can be applied to the monolith. Under this assumption, the higher production rate (11,202 tons per year) and lower cost estimate ($500 per ton) provided by GEOSAFE is used. It is assumed that 2 ISV machines would be required for this treatment train. The high production/low cost assumption provides an annual cost estimate of $11,102,000.

Calculations: 2 ISV machines x 11,202 tons/yr = 22,204 tons/yr
244,245 tons material* ÷ 22,204 tons/yr= 11 yr project life
$11,700,000 capital cost*
22,204 tons/yr x $500/ton = $11,102,000/yr operating cost

* See treatment train #13 for detail.

It is assumed that in situ grouting and ISV can be performed simultaneously and the components commence in year 1. The SDA cap component begins in year 12, once the grouting and ISV projects have been completed.

Monitoring[1]: annual cost = $298,000
net present value = $11,037,037
SDA Cap[2]: total cost = $105,473,000

1. See treatment train #1 for detail.
2. See treatment train #3 for detail.

Treatment train #16: monitoring plus SDA Cap plus gantry retrieval system (mobile retrieval facility (MRF)) plus engineered vaults

Gantry Retrieval System - Mobile Retrieval Facility (MRF)
The **Baseline Report** provided a cost estimate of $32,669,000 for the MRF.

Engineered Vaults
Personnel at the Savannah River Site (SRS) provided cost data developed from their research on engineered vault technology. The cost estimate provided to MSE ($44,800,00) was the total cost for two vaults: a low level vault and a intermediate level vault. $34,000,000 was identified by SRS personnel as the cost of the low level vault and the remainder ($10,800,000) was assumed to be the cost of an intermediate level vault with a 240,000 ft^3 capacity. This $10.8 million estimate included a 15 percent contingency fee which was removed for purposes of this model, yielding a net estimate of $9,180,000 for the intermediate vault. A $38.25 per cubic foot cost was assumed as the engineered vault disposal cost.

Calculation: $9,180,000 vault cost ÷ 240,000 ft^3= $38.25 per ft^3

The **Baseline Report** estimates that the MRF would be operational for 13 years. The **PD Study** provides an estimate of 6,280,214 cubic feet of total waste plus soil intermingled with waste as the amount of material which must be considered for retrieval and treatment options. Therefore, an annual total cost of $18,478,322 for the engineered vaults component is assumed.

Calculations: 6,280,000 ft^3 material ÷ 13 yr life= 483,093 ft^3/yr
483,093 ft^3/yr x $38.25/$ft^3$ = $18,478,322/yr

The SRS document estimated that 26 percent of the total cost is the capital cost component ($4,804,000/yr) and the remaining 74 percent is the operating cost component ($13,674,000/yr).

Finally, it was assumed that the MRF and engineered vault components of this treatment train would be completed in 20 years and the SDA cap component would begin in year 21.

Monitoring[1]: annual cost = $298,000
net present value = $11,037,037
SDA Cap[2]: total cost = $105,473,000

1. See treatment train #1 for detail.
2. See treatment train #3 for detail.

Treatment train #17: monitoring plus SDA Cap plus in situ modular waste retrieval and treatment system (ISMWR) plus engineered vaults

In Situ Modular Waste Retrieval and Treatment System (ISMWR)

Machine Kinetics provided a report which contained cost data for ISMWR (ISMWR Report). The **ISMWR Report** provided the following cost timeline:

Year 1: \$3,325,000 (evaluation of technology)
Year 2: \$3,325,000 (evaluation of technology)
Year 3: \$5,600,000 (selection, preliminary design, prototype design)
Year 4: \$4,200,000 (selection, preliminary design, prototype design)
Year 5: \$40,000,000 (construct ISMWR machine)
Year 6: \$40,000,000 " "
Year 7: \$40,000,000 " "

The **ISMWR Report** estimated a production rate of 66,660 cubic yards per year (179,820 ft^3/yr) which yields a component completion time of 3.5 years.

Calculation: 6,280,214 ft^3 total waste ÷ 179,820 ft^3/yr= 3.5 yr

The end product of the ISMWR system is an encapsulated "block" of waste. This treatment train assumes that once the ISMWR component is completed, the "blocks" of waste would then be put into engineered vaults. The engineered vaults component would begin in year 8 and continue for 4 years. This component would cost \$60,054,000 per year. Twenty six percent of this cost (\$15,614,000) is assumed to be the annual capital cost while the remainder (\$44,440,000) is assumed to be the annual operating cost for the 4 year period. The SDA cap component will begin in year 12.

Calculations: 6,280,000 ft^3 total waste ÷ 4 yr = 1,570,000 ft^3/yr
1,570,000 ft^3/yr x \$38.25/ft^3 = \$60,054,000/yr

Monitoring[1]: annual cost = \$298,000
net present value = \$11,037,037

SDA Cap[2]: total cost = \$105,473,000

1. See treatment train #1 for detail.
2. See treatment train #3 for detail.

Treatment train #18: monitoring plus SDA Cap plus remote excavation plus engineered vaults

Remote Excavation
Two reports were used to gather cost data for this component: the **Remote Excavation System Technology Evaluation Report** (Remote Report) and the **Full Scale Retrieval of Simulated Buried Transuranic Waste** (Manual Report). The **Manual Report** stated that the cost to modify a Caterpillar[R] 325 L excavator for remote operations would range from \$300,000 to \$1,000,000. The high end

figure was chosen. The cost of a 325 L excavator (obtained from a CAT^R vendor) was $218,000. The excavator has an expected life of 10,000 hours.

The **Remote Manual** indicated that the operations cost for a remote excavator is $65/hr and the **Manual Report** provide an estimate of $29/hr materials cost (e.g., fuel, oil, etc.). These two costs yield an assumed $94/hr cost for a remotely operated excavator.

A production rate of 865 ft^3/hr was estimated based upon the following production rates contained in the two reports:

49.4 yd^3/hr (manually operated)
2.4 ft^3/min (remotely operated)
3.7 ft^3/min (manually operated)

<u>Calculations</u>:	2.4 $ft^3 \div$ 3.7 ft^3 = .6486 assumed efficiency
	0.6486 x 49.4 yd^3/hr = 32 yd^3/hr
	32 yd^3/hr x 27 ft^3/yd^3 = 865 ft^3/hr

At a production rate of 865 ft^3/hr it would take 7,260 hours to remotely excavate the SDA area. This estimated time is well within the 10,000 hour life expectancy of the excavator.

<u>Calculation</u>: 6,280,214 ft^3 total waste $\div$ 865 ft^3/hr = 7,260 hr

The cash flow stream for this component is assumed to be:

Year 1:	$1,218,000 capital cost
	$188,000 operating cost
Year 2:	$188,000 operating cost
Year 3:	$188,000 operating cost
Year 4:	$118,000 operating cost

<u>Calculations</u>:	assumed an 8 hour day
	8 hr/day x 250 days/yr = 2,000 hr/yr
	7,260 yrs $\div$ 2,000 hr/yr = 3.63 years to complete component
	2,000 hr/yr x $94/hr = $188,000/yr operating cost
	Year 4 operating cost= .63 year x $188,000/yr = $118,000

The engineered vaults component of this treatment train is assumed to run concurrently with the remote excavation in years 1 through 4. The SDA cap component is assumed to begin in year 5.

Monitoring[1]:	annual cost = $298,000
	net present value = $11,037,037

SDA Cap[2]: total cost = $105,473,000

Engineered vaults[3]: capital cost = $15,614,000/yr
operating cost = $44,440,000/yr

1. See treatment train #1 for detail.
2. See treatment train #3 for detail.
3. See treatment train #17 for detail.

Treatment train #19: monitoring plus SDA Cap plus Gantry retrieval plus ISV

Cash flows from the **Baseline Report** were used as the annual capital cost for the Gantry system in years 1 through 7. The Gantry retrieval and ISV operations are assumed to run concurrently and begin in year 8 and continue for 13 years. It was assumed that 2 ISV machines (housed in one building) could perform the required melts.

Monitoring[1]: annual cost = $298,000
net present value = $11,037,037

SDA Cap[2]: total cost = $105,473,000
Gantry Retrieval[3]: operating cost = $4,932,000/yr

ISV[4]: capital cost = $11,700,000
operating cost[5] = $9,394,000/yr

1. See treatment train #1 for detail.
2. See treatment train #3 for detail.
3. See **Baseline Report** for detail.
4. See treatment train #13 for detail.
5. See treatment train #15 for detail. Note: treatment train #19 assumes a 13 year component life using the lower end ISV cost estimate ($500/ton) whereas treatment train #15 assumes a 20 year component life.

Treatment train #20: monitoring plus SDA Cap plus Gantry retrieval plus ISG

Assumptions regarding the Gantry system in this component are identical to the assumptions indicated in treatment train #19. Furthermore, it is assumed that ISG and the Gantry process can occur simultaneously, beginning in year 8.

Monitoring[1]: annual cost = $298,000
net present value = $11,037,037

SDA Cap[2]: total cost = $105,473,000

Gantry Retrieval[3]: operating cost = \$4,932,000/yr
ISG[4]: operating cost = \$9,046,000/yr

1. See treatment train #1 for detail.
2. See treatment train #3 for detail.
3. See **Baseline Report** for detail.
4. See treatment train #14 for detail. Note: Treatment train #14 assumes a component life of 10 years whereas treatment train #20 assumes a 13 year component life.

Treatment train #21: monitoring plus SDA Cap plus ISMWR plus ISV

This treatment train is similar to train #19, except that ISMWR is substituted for the Gantry process. ISMWR and ISV operations will begin in year 8. ISMWR will take 3.5 years to complete while ISV will take 11 years for completion. Once ISV operations have concluded, then the SDA cap will be installed.

Monitoring[1]: annual cost = \$298,000
net present value = \$11,037,037

SDA Cap[2]: total cost = \$105,473,000

ISMWR[3]: Year 1: \$3,325,000 (evaluation of technology)
Year 2: \$3,325,000 (evaluation of technology)
Year 3:\$5,600,000(selection, preliminary design, prototype design)
Year 4:\$4,200,000 (selection, preliminary design,prototype design)
Year 5: \$40,000,000 (construct ISMWR machine)
Year 6: \$40,000,000 " "
Year 7: \$40,000,000 " "
annual operating cost[4]: \$13,328,000 (years 8 - 10)
\$6,664,000 (year 11)

ISV[5]: capital cost = \$11,700,000
operating cost[6] = \$11,102,000/yr

1. See treatment train #1 for detail.
2. See treatment train #3 for detail.
3. See treatment train #17 for detail.
4. See **ISWMR** report for detail.
5. See treatment train #13 for detail.
6. Assumes an 11 year component life.

Treatment train #22: monitoring plus SDA Cap plus ISMWR plus ISG

Monitoring[1]: annual cost = $298,000
net present value = $11,037,037

SDA Cap[2]: total cost = $105,473,000

ISMWR[3]: Year 1: $3,325,000 (evaluation of technology)
Year 2: $3,325,000 (evaluation of technology)
Year 3: $5,600,000 (selection, preliminary design prototype design)
Year 4: $4,200,000 (selection, preliminary design, prototype design)
Year 5: $40,000,000 (construct ISMWR machine)
Year 6: $40,000,000 " "
Year 7: $40,000,000 " "

annual operating cost[4]: $13,328,000 (years 8 - 10)
$6,664,000 (year 11)

ISG[4]: operating cost = $9,046,000/yr

1. See treatment train #1 for detail.
2. See treatment train #3 for detail.
3. See treatment train #17 for detail.
4. See treatment train #14 for detail. Note: Treatment train #14 assumes a component life of 10 years whereas treatment train #22 assumes a 11 year component life.

Treatment train #23: monitoring plus SDA Cap plus remote excavation plus ISV

Remote excavation was first introduced in treatment train #18. In train #18, remote excavation was assumed to be a single unit operation (e.g., excavate waste/soil and place the mixture into engineered vaults) which took 3.63 years to complete. In treatment train #23 however, it is assumed that the remote excavation component involves 3 unit operations: excavation of a staging hole, placement of material into the staging hole, and mixing the material. The assumed component completion time for train #23 is therefore 3 times longer (11 years) than the assumed time in train #18. Also, the remote excavation machine is assumed to be replaced in year six due to the expected life restriction of 10,000 hours. The SDA cap component will begin once the ISV component is complete.

Monitoring[1]: annual cost = $298,000
net present value = $11,037,037

SDA Cap[2]: total cost = $105,473,000
Excavation[3]: capital cost = $1,218,000 (years 1 & 6 of component period)
annual O&M cost = $188,000/yr

ISV[4]: capital cost = $11,700,000
annual O&M cost = $11,102,000/yr

1. See treatment train #1 for detail.
2. See treatment train #3 for detail.
3. See treatment train #18 for detail.
4. See treatment train #14 for detail. Note: train #23 assumes an 11 year component completion time span.

Treatment train #24: monitoring plus SDA Cap plus remote excavation plus ISG

Monitoring[1]: annual cost = $298,000
net present value = $11,037,037

SDA Cap[2]: total cost = $105,473,000
Remote Excavation[3]: capital cost= $1,218,000 (years 1 & 6 of component period)
annual O&M cost = $188,000/yr
ISG[4]: annual O&M cost = $11,760,000/yr

1. See treatment train #1 for detail.
2. See treatment train #3 for detail.
3. See treatment train #18 for detail.
4. See treatment train #14 for detail.

Treatment train #25: Gantry building, chemical pretreatment, plasma furnace, and WIPP disposal (Baseline)

This treatment train uses the cost estimates provided in the **Baseline Report** plus WIPP disposal costs of $26,740,000 per year for 13 years. This annual cost is added to WBS 133.

Calculations: 49,500 drums[1] over the course of 13 yrs
49,500 drums ÷ 13 yrs = 3,808 drums/yr
$7,022/drum disposal cost[2] x 3,808 drum/yr
= $26,740,000/yr

1. See **Baseline Report - WBS 133**.
2. Cost quote from WIPP.

Treatment train #26: Gantry building, segmented gate, plasma furnace, and WIPP disposal

The cost estimates for this treatment train are based on a slightly modified version of the **Baseline Report**. The modifications are twofold: chemical treatment costs are "backed out" of WBS 122 and a segregated gate component cost is added to WBS 131.

The **Baseline Report** estimates a chemical treatment capital cost of $141,900,000 over the course of a 7 year construction period. However, closer inspection indicated that the bulk of the capital costs occur in the middle 5 years (years 2 through 6). Therefore, $28,380,000/yr were "backed out" of WBS 122 for this 5 year period.

Calculation: $141,900,000 ÷ 5 yr = $28,380,000/yr

Other costs associated with chemical treatment were "backed out" as well. These include: operations labor (WBS 131): $1,602,000/yr for 13 years utilities (WBS 132): chemicals not used (nitric acid, sulfuric acid, TEA, caustic acid, oxalic acid, cerium nitrate, sodium hydroxide (3/4 of total cost).

Total = $4,286,000/yr for 13 yrs.

Segregated Gate

A vendor quoted a cost of $75/yd^3 for a segregated gate system operating in an environment characterized by "a simple, clean operation with material fed continuously around the clock". Since this quote was for a simple system with no problems, the assumed processing cost for this component was 3 times the quoted cost ($225/yd^3). This assumed processing cost added $4,024,000/yr to the costs in WBS 131 for a 13 year time period.

Calculations:

$225/yd^3 ÷ 27 ft^3/yd^3 = $8.33/ft^3
6,280,214 ÷ 13 yr component life = 483,093 ft^3/yr
483,093 ft^3/yr x $8.33/ft^3 = $4,024,000/yr

Treatment train #27: Full vitrification - Gantry building, plasma furnace, and WIPP disposal

Train #27 is comprised of treatment train #26 plus processing 100 percent of the treated material through multiple vitrification units. The **Baseline Report** indicated that 2,000 pounds per hour of waste could be processed per vitrification unit. Over a 13 year time period, 57,330 tons would be treated by one vitrification unit.

Calculations: 2,000 lb/hr x 4,410 hr/yr = 8,820,000 lb/yr

8,820,000 lb/yr ÷ 2,000 lb/ton = 4,410 tons/yr
4,410 tons/yr x 13 yr=57,330 tons

Calculations provided in treatment train #13 indicate a total tonnage of soil and waste in the amount of 244,245 tons. Based on this total tonnage estimate, a melter capacity ratio was calculated to determine how many additional melters would have to be installed to complete the project in 13 years. The estimated capacity ratio was 4.26.

Calculation: 244,245 tons ÷ 57,330 tons = 4.26

This ratio indicates that 4.26 additional melters would be required. A total installed cost of $51,000,000 per melter was obtained from the **Baseline Report**. This resulted in an additional capital cost of $217,277,000 which was spread out over the 5 major construction years (years 2 - 6) of WBS 122. Once the cost of one melter was backed out of the figures from the **Baseline Report,** an additional $33,255,000 per year was added to WBS 122.

Calculations: $51,000,000 x 4.26 = $217,277,000 cost

$217,277,000 ÷ 5 construction yrs= $43,455,000/yr
$51,000,000 ÷ 5 yrs = $10,200,000/yr
(this cost was already included in WBS 122)
$43,455,000/yr - $10,200,000/yr= $33,255,000/yr

The additional melters require an additional labor expense (melting and drum handling) of $5,357,000 per year in WBS 131.

Calculations: $1,643,200/yr labor cost x 4.26= $7,000,000/yr
$7,000,000 - $1,643,200 (already included in WBS 131)
= $5,351,000/yr for 13 years

Finally, the following components of WBS 132 were all increased by the capacity ratio (4.26) to account for the additional melters and the resultant additional costs: electricity, propane, nitrogen, barrels, waste boxes, and transfer modules. These increases resulted in a $19,945,000 per year added to WBS 132.

Treatment train #28: Gantry building, incineration, and ash disposal to WIPP

This treatment train assumes that ash would be shipped to the WIPP instead of glass as was the case in train #25. The bulk density difference between glass (200 lb/ft^3) and ash (50 lb/ft^3) is 150 lb/ft^3. This indicates that 4 times as many drums would be required than the estimated 3808 drums per year in train #25. Therefore, an additional $2,640,000/yr for 13 years was added to WBS 133.

The **Baseline Report** stated that a melter unit would cost $22,000,000. An advanced electric reactor incinerator is assumed to replace the aforementioned melter in this treatment train. A $4,201,000 incinerator cost was developed from the **ECHOS Costbook**. The cost differential between the two machines resulted in a net savings of $3,560,000 per year for 5 years. This savings was "backed out" of WBS 122.

<u>Calculations</u>: $22,000,000 - $4,201,000 = $17,800,000 machine cost savings
$17,800,000 ÷ 5 yr construction = $3,560,000/yr

Appendix K: Values for Each Objective

The following tables present the output results from the Logical Decisions and DPL models. Table K.1 provides the CERCLA balancing criteria values, while the remaining tables show the component values associated with each train for each goal (or measure). For example, table K.1 shows that train #1 ranked 20th overall with an overall value of 4.826. The overall value is a result of the following CERCLA criteria values: implementability (7.5), short-term effectiveness (7.5), long-term effectiveness (1.01), reduction of toxicity, mobility, or volume through treatment (0), and cost (9.94). These values were multiplied by their respective weights (1/6, 1/6, 1/4, 1/4, and 1/6) to determine the overall value.

Table K.1 Overall value, balancing criteria values and ranking.

Name	Overall Rank	Overall Value	Imp	Short-Term	Long-Term	Reduction	Cost
Overall Wt			1/6	1/6	1/4	1/4	1/6
Train #1	20	4.826	10	7.5	1.01	0	9.94
Train #2	23	4.67	9.167	7.4	1.01	0	9.938
Train #3	16	5.439	8.417	9.137	3.785	0	9.4
Train #4	10	5.817	6.452	7.275	5.21	2.922	8.979
Train #5	15	5.571	6.509	6.007	5.21	2.922	8.709
Train #6	9	5.899	7.438	7.375	4.61	2.922	9.281
Train #7	8	5.902	6.835	7.162	5.385	2.922	8.955
Train #8	12	5.68	6.926	6.007	5.385	2.922	8.686
Train #9	6	5.994	7.771	7.375	4.785	2.922	9.258
Train 10	7	5.945	6.938	7.262	5.385	2.922	9.008
Train 11	11	5.707	6.935	6.107	5.385	2.922	8.739
Train 12	5	6.093	8.208	7.475	4.785	2.922	9.311
Train 14	13	5.636	7.125	6.825	5.16	2.056	9.042
Train 15	1	7.104	4.552	6.412	7.285	8.206	8.425
Train 16	27	4.159	4.17	4.215	5.535	0	8.267
Train 17	26	4.445	5.84	4.812	5.535	0	7.715
Train 18	25	4.495	4.837	5.6	5.535	0	8.233
Train 19	4	6.608	3.752	4.215	7.285	8.328	8.263
Train 20	24	4.559	2.337	4.215	5.785	2.239	8.768
Train 21	3	6.71	4.337	4.232	7.285	8.328	8.271
Train 22	22	4.703	3.657	4.25	5.785	2.239	8.277
Train 23	2	6.865	4.052	4.812	7.285	8.328	8.904
Train 24	21	4.822	3.003	4.925	5.785	2.239	8.968
Train 25	17	5.385	2.4	2.707	7.285	8.794	3.083
Train 26	14	5.603	2.9	2.707	7.285	8.839	3.825
Train 27	18	5.367	3.533	2.707	7.285	8.756	1.9
Train 28	19	4.934	3.333	2.707	7.285	8.422	0

Table K.2 Implementability component values and ranking.

Name	Imp Rank	Ability to Construct	Rel & Avail of Tech	Equipment & Service	Storage & Disposal	Admin Feasibility
Overall wt		1/36	1/36	1/36	1/36	1/18
Train #1	1	10	10	10	10	10
Train #2	2	5	10	10	10	10
Train #3	3	2.5	10	10	10	9
Train #4	13	0.312	7	6	10	7.7
Train #5	12	0.156	7.5	6	10	7.7
Train #6	6	0.625	8	10	10	8
Train #7	11	0.312	8.3	6	10	8.2
Train #8	10	0.156	9	6	10	8.2
Train #9	5	0.625	9	10	10	8.5
Train 10	8	0.625	8	6	10	8.5
Train 11	9	0.312	8.3	6	10	8.5
Train 12	4	1.25	10	10	10	9
Train 14	7	1.25	7.5	8	10	8
Train 15	16	0.312	5	2	10	5
Train 16	18	0.02	6	4	0	7.5
Train 17	14	0.039	10	10	0	7.5
Train 18	15	0.02	8	6	0	7.5
Train 19	20	0.01	5.5	2	10	2.5
Train 20	27	0.02	5	4	0	2.5
Train 21	17	0.02	9	2	10	2.5
Train 22	21	0.039	8.9	8	0	2.5
Train 23	19	0.01	7.3	2	10	2.5
Train 24	24	0.02	7	6	0	2.5
Train 25	26	0	1.4	4	9	0
Train 26	25	0	1.4	4	9	1.5
Train 27	22	0	5.2	4	9	1.5
Train 28	23	0	3	4	9	2

Table K.3 Short-term effectiveness component values and ranking.

Name	STE Rank	Time	Com Prot	Work Prot	Plant Impact	Animal Impact
overall wt		1/24	1/24	1/24	1/48	1/48
Train #1	2	0	10	10	10	10
Train #2	4	0	10	9.6	10	10
Train #3	1	7.75	10	8.8	10	10
Train #4	7	5.5	6	7.6	10	10
Train #5	13	0.83	6	7.2	10	10
Train #6	5	5.5	6	8	10	10
Train #7	9	5.05	6	7.6	10	10
Train #8	13	0.83	6	7.2	10	10
Train #9	5	5.5	6	8	10	10
Train 10	8	5.05	6	8	10	10
Train 11	12	0.83	6	7.6	10	10
Train 12	3	5.5	6	8.4	10	10
Train 14	10	3.7	6	7.6	10	10
Train 15	11	3.25	6	6.4	10	10
Train 16	21	0.861	4	2	10	10
Train 17	17	3.25	4	2	10	10
Train 18	15	6.4	4	2	10	10
Train 19	21	0.861	4	2	10	10
Train 20	21	0.861	4	2	10	10
Train 21	20	0.928	4	2	10	10
Train 22	19	1	4	2	10	10
Train 23	17	3.25	4	2	10	10
Train 24	16	3.7	4	2	10	10
Train 25	24	0.83	0	0	10	10
Train 26	24	0.83	0	0	10	10
Train 27	24	0.83	0	0	10	10
Train 28	24	0.83	0	0	10	10

Table K.4 Long-term effectiveness component values and ranking.

Name	LTE Rank	Resid Risk	Mgt Req	Rel of Mgt Cont
overall wt		1/8	1/16	1/16
Train #1	26	0	4.04	0
Train #2	26	0	4.04	0
Train #3	25	5	2.14	3
Train #4	19	6.2	1.44	7
Train #5	19	6.2	1.44	7
Train #6	24	5.5	1.44	6
Train #7	15	6.2	2.14	7
Train #8	15	6.2	2.14	7
Train #9	22	5.5	2.14	6
Train 10	15	6.2	2.14	7
Train 11	15	6.2	2.14	7
Train 12	22	5.5	2.14	6
Train 14	21	6	2.14	6.5
Train 15	1	9	2.14	9
Train 16	12	7	2.14	6
Train 17	12	7	2.14	6
Train 18	12	7	2.14	6
Train 19	1	9	2.14	9
Train 20	9	7	2.14	7
Train 21	1	9	2.14	9
Train 22	9	7	2.14	7
Train 23	1	9	2.14	9
Train 24	9	7	2.14	7
Train 25	1	9	2.14	9
Train 26	1	9	2.14	9
Train 27	1	9	2.14	9
Train 28	1	9	2.14	9

Table K.5 Reduction of toxicity, mobility, or volume through treatment component values and ranking.

Name	Reduce Rank	Amnt PT Treat	Irrevers	Red PT	Vol of Treat Resid	Red Mob to Air	Red Mob to GW	Reduce Tox
overall wt		1/12	1/12	1/72	1/72	1/72	1/72	1/36
Train #1	22	0	0	0	0	0	0	0
Train #2	22	0	0	0	0	0	0	0
Train #3	22	0	0	0	0	0	0	0
Train #4	9	1.7	1.7	3	10	7.5	1.7	5
Train #5	9	1.7	1.7	3	10	7.5	1.7	5
Train #6	9	1.7	1.7	3	10	7.5	1.7	5
Train #7	9	1.7	1.7	3	10	7.5	1.7	5
Train #8	9	1.7	1.7	3	10	7.5	1.7	5
Train #9	9	1.7	1.7	3	10	7.5	1.7	5
Train 10	9	1.7	1.7	3	10	7.5	1.7	5
Train 11	9	1.7	1.7	3	10	7.5	1.7	5
Train 12	9	1.7	1.7	3	10	7.5	1.7	5
Train 14	21	1.7	1.7	0	9.9	5	1.7	0
Train 15	8	8.5	8.5	2	9.8	9	9.9	7.5
Train 16	22	0	0	0	0	0	0	0
Train 17	22	0	0	0	0	0	0	0
Train 18	22	0	0	0	0	0	0	0
Train 19	5	8.5	8.5	3.5	9.8	9.7	9.9	7.5
Train 20	18	1.7	1.7	0	9.9	5	5	0
Train 21	6	8.5	8.5	3.5	9.8	9.7	9.9	7.5
Train 22	18	1.7	1.7	0	9.9	5	5	0
Train 23	7	8.5	8.5	3.5	9.8	9.7	9.9	7.5
Train 24	18	1.7	1.7	0	9.9	5	5	0
Train 25	2	8.5	8.5	9	7.5	9.8	10	10
Train 26	1	8.5	8.5	7.5	9.8	9.8	10	10
Train 27	3	8.5	8.5	6	9.8	9.8	10	10
Train 28	4	8.5	8.5	0	9.8	9.8	10	10

Appendix L: Weight Sensitivity Analysis

Figures L.1 - L.5 show how insensitive the top ranked train (train 15) is to changes in the nominal values of the weights given to the five CERCLA criteria. These graphs show how the total value of each train, scoring greater than five in nominal overall value, changes as the weight associated with a specific balancing criterion changes. In each graph the weight of a specific criterion is moved from 0 to 100 % of the total weight. The vertical line in each figure represents the nominal weight. As the weight of the selected criterion increases, the weights associated with the other criteria decrease proportionally. Changes in the criteria weights change the overall value for each train.

These graphs are not intended to show the value of a specific train when the weight associated with a specific criterion is changed. Rather, these graphs show where changes in the top ranked train occur. In each graph, train 15 has the greatest overall value for the current setting of the weights (the vertical line). As long as train 15 is the highest line on the graph, it has the greatest overall utility. However, whenever the train 15 line crosses paths with another line, then the alternative associated with that line becomes the train with the greatest overall value. The key to the right of each graph is ordered in decreasing overall value based on the nominal weights.

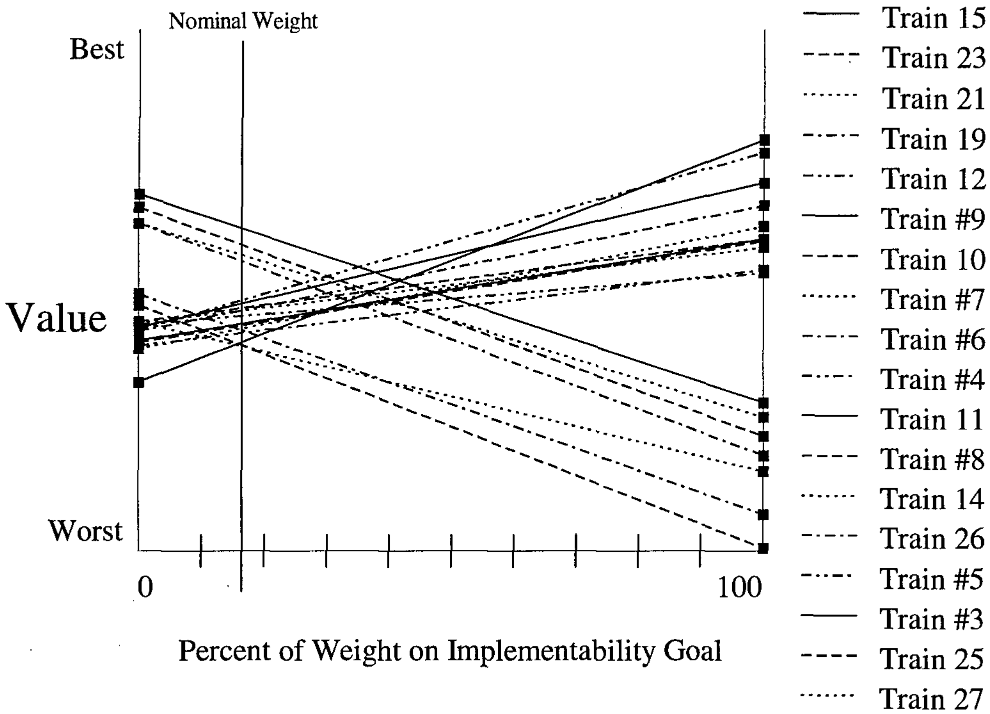

Figure L.1 Sensitivity analysis on implementability weight.

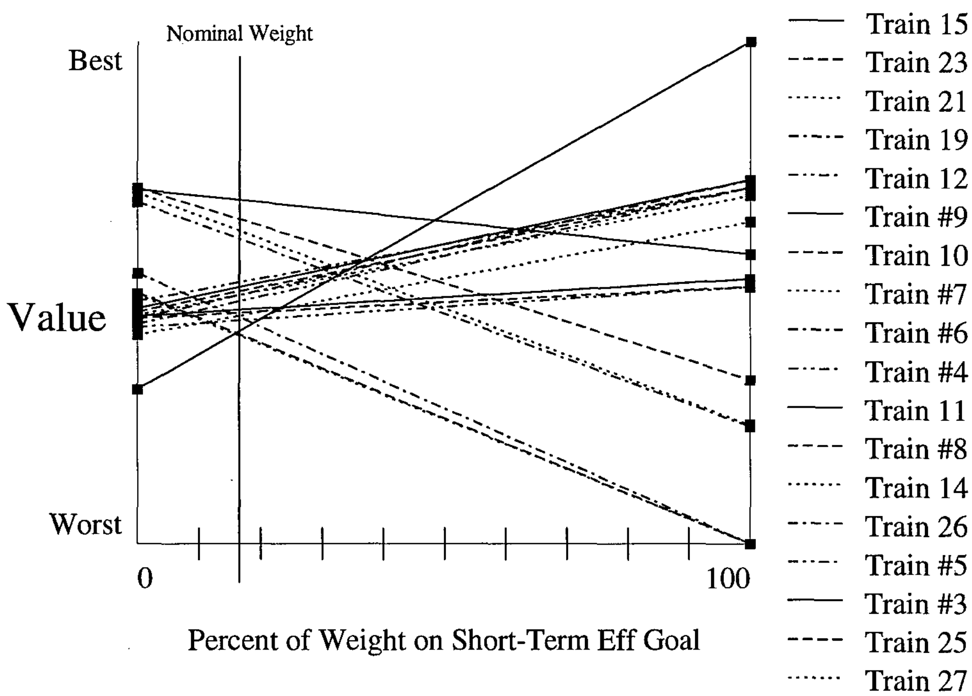

Figure L.2 Sensitivity analysis on short-term effectiveness weight.

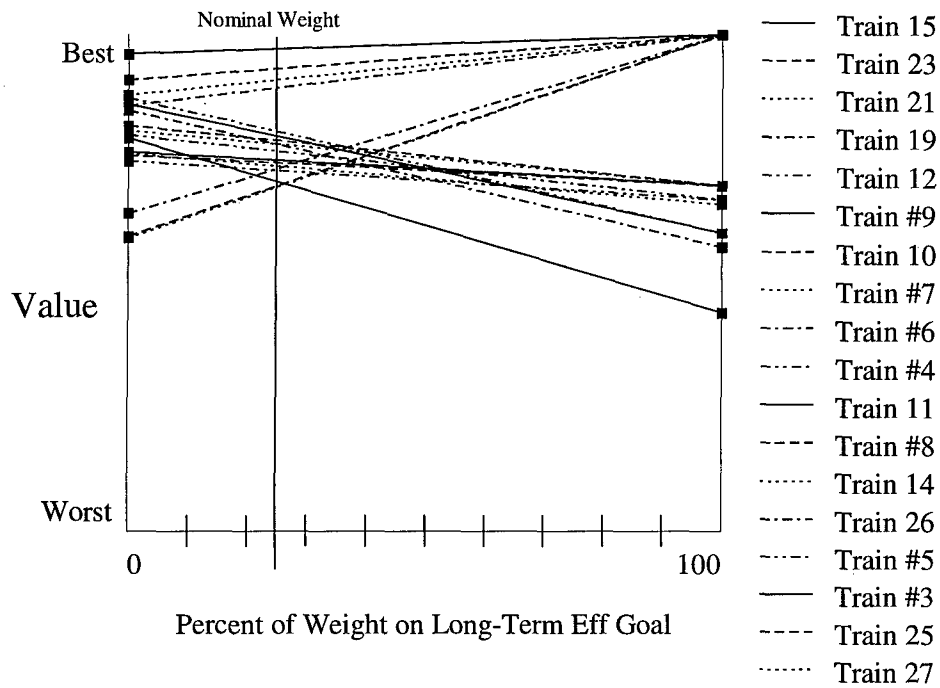

Figure L.3 Sensitivity analysis on long-term effectiveness weight.

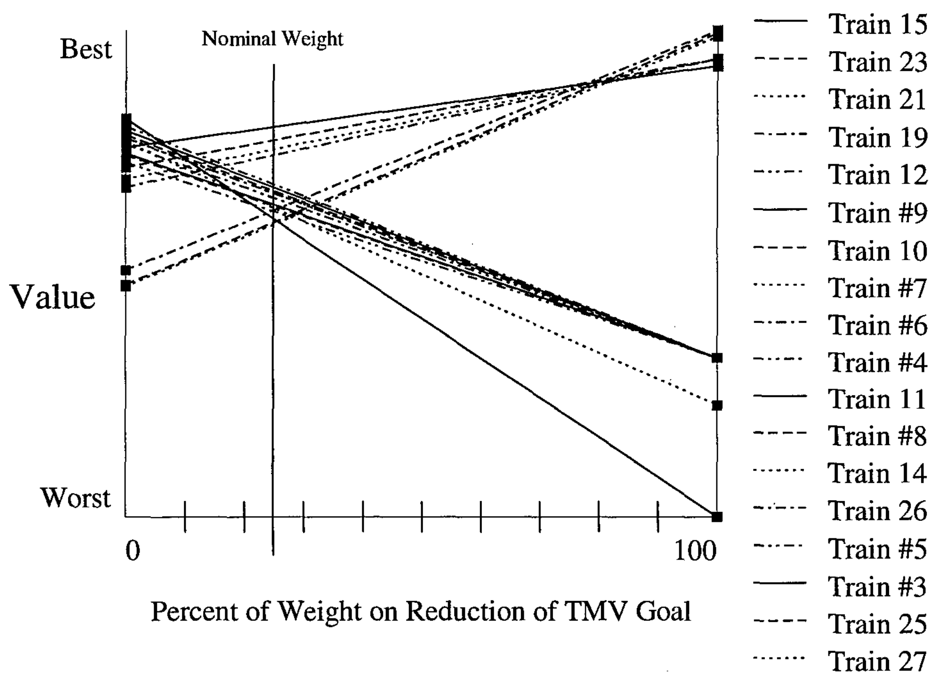

Figure L.4 Sensitivity analysis on reduction of toxicity, mobility, or volume weight.

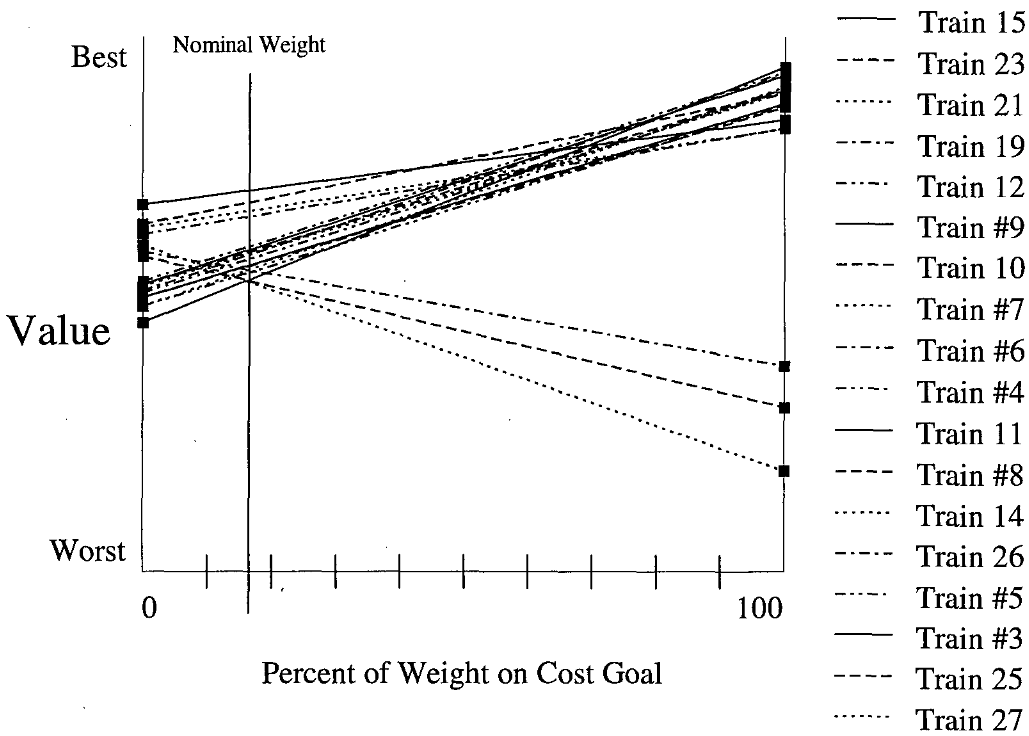

Figure L.5 Sensitivity analysis on cost weight.

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Vita

Lt Brian Grelk[redacted]. He graduated from Junction City High School in 1990 and attended Kansas State University in Manhattan, Kansas. He graduated Magna Cum Laude with a Bachelor of Science degree in Nuclear Engineering and received his reserve commission in May 1995. In August 1995 he married Mary Louise Jesch and entered the School of Engineering at the Air Force Institute of Technology (AFIT). On October 24, 1995 he received his regular commission. Lt Grelk's follow-on assignment was to the 422 Testing and Evaluation Squadron at Nellis Air Force Base in Las Vegas, Nevada.

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13. ABSTRACT *(Maximum 200 words)*

The Idaho National Environmental Engineering Laboratory (INEEL), operating in conjunction with the Department of Energy (DOE), faces with the complex decision of selecting an environmental remediation strategy for the Subsurface Disposal Area (SDA) of the Radioactive Waste Management Complex (RWMC). This research uses value-focused thinking and multiattribute preference theory techniques to produce a decision analysis model to aid the decisionmakers as they select a remediation strategy. A deterministic analysis using expert opinion and the best available engineering data demonstrates the model's capabilities. The model ranks 27 specific remediation strategies based on how well they meet CERCLA's five balancing criteria: implementability, short-term effectiveness, long-term effectiveness, reduction of toxicity, mobility, or volume through treatment, and cost. The model allows for sensitivity analysis to display the effects of changes in engineering opinion, the values of the data, and model parameters. Overall, the model provides decision tools that can help the decisionmakers at INEEL make a better informed and better documented decision when choosing a remediation strategy. Furthermore, the model can be easily manipulated and applied by decision-makers at other DOE sites.

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